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OPTIMIZATION OF THIN-FILM TRANSPARENT
PLASTIC HONEYCOMB COVERED FLAT-PLATE
SOLAR COLLECTORS

Lockheed Missiles & Space Company, Inc.
Palo Alto, California

25 May 1978

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**OPTIMIZATION OF THIN-FILM TRANSPARENT PLASTIC HONEYCOMB
COVERED FLAT-PLATE SOLAR COLLECTORS**

Final Report

**May 25, 1978
Date Published**

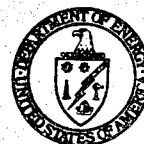
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**Lockheed Missiles & Space Company, Inc.
Palo Alto Research Laboratory
Palo Alto, California**



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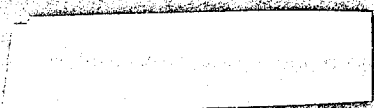
Solar Energy

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OPTIMIZATION OF THIN-FILM TRANSPARENT
PLASTIC HONEYCOMB COVERED FLAT-PLATE
SOLAR COLLECTORS

FINAL REPORT

LOCKHEED MISSILES & SPACE COMPANY, INC.
PALO ALTO RESEARCH LABORATORY
3251 Hanover Street
Palo Alto, California 94304

Date Published - 25 May 1978

PREPARED FOR THE UNITED STATES
ENERGY RESEARCH AND DEVELOPMENT
ADMINISTRATION
DIVISION OF SOLAR ENERGY

UNDER CONTRACT NO. E(04-3)-1256

ABSTRACT

An analytical and experimental program was conducted to develop an optimized transparent plastic honeycomb for use in a flat-plate solar collector system. Analysis was performed on both low- and high-temperature candidate plastics from the point of view of ease of manufacture, performance, and total cost. Detailed testing was performed on two candidate honeycomb materials - Mylar and Lexán - using Glass, Tedlar, and Teflon as the cover materials. Although a Teflon system gave a high collector performance, difficulty in manufacture and high material costs ruled out the possible economical use of the system at present. The Lexan/Glass and Lexan/Tedlar system of honeycomb/cover gave similar results which were higher than those for the Mylar systems. A thermal protection technique was developed for the "coolant stagnation" situation, in which the honeycomb was raised above the absorber plate surface.

SUMMARY

This program was directed toward the development and optimization of transparent plastic honeycombs for incorporation into high-performance flat-plate solar collectors. Analytical and experimental studies were conducted with respect to a variety of plastic materials suitable for both high- and low-honeycomb service temperatures. Two commercial processes were used to fabricate honeycomb test specimens: expanded cell film layup (Hexcel Corporation, Dublin, California) and thermal forming (Norfield Corporation, Danbury, Connecticut). Mylar and Lexan honeycombs were tested in full-scale solar collectors in conjunction with various glass and plastic cover materials. Methods of protecting plastic honeycombs from thermal degradation under stagnation conditions were studied, and the most promising approach was experimentally evaluated. The analytical and experimental results were used to define an optimum system in terms of performance and cost parameters.

The program philosophy was to approach the optimization of the total honeycomb-covered flat-plate solar collector system in terms of four interrelated task areas:

- Task 1: Evaluation of the feasibility of utilizing FEP Teflon as a transparent cover and cellular structure
- Task 2: Optimization of low-temperature plastic honeycombs
- Task 3: Plastic cover/plastic honeycomb collector studies
- Task 4: Thermal protection methods for low-temperature plastic honeycombs

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The work was under the direction of Dr. M. McCargo and K. N. Marshall, Program Managers; technical effort by Dr. S. A. Greenberg, R. Wedel, and R. Dammann; and Professor K. G. T. Hollands, Waterloo University, Ontario, Canada, acted as consultant on the program.

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- A.2 "Economic Studies of Plastic Honeycomb Solar Collectors," by K. N. Marshall, R. K. Wedel, and K. G. T. Hollands, Proceedings of 1977 Flat Plate Solar Collector Conference, Feb. 28-Mar 2, 1977, Orlando, Fla, pp 653-662 A.2-1
- A.3 "A Detailed Model of Flat Plate Solar Collectors," by R. K. Wedel, Proceedings of 1977 ISES Annual Meeting, American Section, Jun 1977, pp 1-1 through 1-6 A.3-1
- A.4 "An Approximate Equation for Predicting the Solar Transmittance of Transparent Honeycombs," by K. G. T. Hollands, K. N. Marshall, and R. K. Wedel, Proceedings of 1977 ISES Annual Meeting, American Section, Jun 1977, pp 4-1 through 4-5 A.4-1
- A.5 "Use of Lexan and Kapton Honeycombs to Increase Solar Collector Efficiency," by K. N. Marshall and R. K. Wedel, AI Chem. E. Symposium Series, No. 164, Vol. 73 pp 155-162 A.5-1
- A.6 "Experimental Performance of Flat Plate Solar Collectors With Various Cover Materials With and Without Transparent Plastic Honeycomb," by R. K. Wedel, R. E. Dammann, and S. A. Greenberg, AIAA Paper 78-899 A.6-1

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Section 1

INTRODUCTION

Wide-scale implementation of solar energy for building heating and cooling applications requires continued development to improve efficiencies and reduce costs of the various components. In this regard, a component of major importance is the solar collector which represents a significant portion of the overall system cost. Various methods for improving the cost effectiveness of the conventional flat-plate solar collector are being studied. Among these is the use of honeycomb to reduce the convective and radiative heat losses.

The technical feasibility of using transparent honeycomb between the absorber plate and glazing to reduce heat losses has been demonstrated. Within the past three years, work performed by Hollands et al. on free convection suppression (Ref. 1), by Buchberg et al. on glass honeycomb (Ref. 2), and by Marshall et al. on plastic honeycomb (Ref. 3), through ERDA-sponsored research and development programs, has shown that the efficiency of flat-plate collectors can be substantially improved by placing transparent honeycomb between the absorber plate and the glazing. The honeycomb improves collector performance by suppressing the radiation and convection heat losses without significantly reducing the amount of incoming solar energy. These studies have also shown that honeycomb collectors have the potential for being cost-effective.

Although technical feasibility has been established by these previous studies, many practical problems remained to be solved. Optimization of cell geometry, selection of the best materials and material thicknesses, and development and implementation of manufacturing methods for cost-effective production represented some of the areas requiring additional work. The present program as reported herein was undertaken to solve many of these problems as applicable to transparent plastic honeycomb.

The present contract is Phase II of a research program to develop high-performance solar collectors for operation in the temperature range of 355 K (130° F) using thin-film transparent plastic honeycombs. Phase I of the program was completed in April 1976 (Ref. 3). During Phase I, a number of plastic materials including Mylar,* Tedlar,* Lexan,** Kapton,* and Teflon* were evaluated for use in collector design. Their optical and thermal properties were determined, and performance characteristics of collectors using these materials were established on the basis of analytical models.

A number of honeycomb solar collectors were fabricated and tested under ambient weather conditions. These tests showed that properly designed plastic honeycomb can produce significant improvements in collector performance compared to non-honeycomb designs. It was also demonstrated that plastic honeycomb collectors provide a potential for lower cost solar collector systems.

Phase I of the program also led to identification of some very real problems associated with the use of plastic honeycombs. Problems in such areas as temperature and ultraviolet (UV) stability, mass production manufacturing, and manufacturing and material costs had to be solved before wide-scale usage of honeycomb collectors could become a reality. To find solutions to these problems required evaluation of different materials, reduced film thicknesses, alternate honeycomb geometrics and configurations, and new fabrication techniques. With these problems in mind, the present program was initiated.

*duPont product.

**General Electric product.

Section 2

PROGRAM OBJECTIVES

The objectives of this program were to develop an optimized transparent plastic honeycomb-covered flat-plate solar collector with improved high-temperature performance and stability, and to reduce honeycomb collector costs through judicious selection of materials, cellular structure configurations, and fabrication techniques.

To achieve these objectives, four tasks were identified and carried out according to the following task breakdown:

- Task 1: Analytical and experimental studies to determine the technical and economic feasibility of utilizing FEP Teflon as a honeycomb structure and transparent cover to increase collector performance and provide high temperature stability.
- Task 2: Analytical and experimental studies to optimize the configuration of low-cost, low-temperature transparent plastic honeycomb (e.g., Lexan and Mylar) for solar collector applications and investigate alternate methods for fabricating plastic cellular structures in order to reduce manufacturing costs.
- Task 3: Analytical and experimental studies to evaluate the use of transparent plastic cover materials over plastic honeycomb systems to increase efficiency and reduce collector cost.
- Task 4: Analytical studies to determine practical methods for protecting low-cost, low-temperature plastic honeycomb materials such as Lexan and Mylar from the high absorber plate temperatures that may be encountered during no-flow conditions.

Section 3

TECHNICAL PROGRAM

Although the potential for increasing the efficiency of a flat-plate solar collector utilizing a transparent plastic honeycomb has been well established, no suitable honeycomb material has been made available commercially. Recognizing this need, a development and evaluation technical program was proposed and executed to provide the required data.

Four major task areas were identified as being the pertinent areas to pursue and the results are detailed below.

3.1 EVALUATION OF THE FEASIBILITY OF UTILIZING FEP TEFLON AS A TRANSPARENT COVER AND CELLULAR STRUCTURE

3.1.1 FEP Teflon Honeycomb

The advantages and feasibility of using an FEP Teflon honeycomb in a flat-plate collector have been reported previously (Ref. 4). The technology presently exists to make such a honeycomb by three different processing techniques: film layup; heat sealing; and thermoplastic forming. The Hexcel Corporation and the Norfield Corporation have both been involved in the investigation of the use of FEP Teflon as a possible honeycomb material. In both processes difficulties were encountered which pointed up the need for further development work to be done. Material cost was also a major concern in the use of FEP Teflon.

In the case of the Norfield Corporation, the existing equipment was not designed to operate at the melt temperature of the Teflon so that extra heater elements were added which resulted in an equipment overheating problem. During the forming of the honeycomb, surface release problems were also encountered which resulted in cell wall

thickening and distortion as shown in Fig. 3-1. Generally, the samples had a nominal wall thickness of 0.054 cm (20 mils), resulting in a decrease in the normal transparency of the Teflon in the visible spectrum. Norfield estimates the cost of Teflon honeycomb would be \$137/m², requiring a starting thickness of 0.203 cm (0.080 in.).

The Hexcel Corporation, which participated in the program using an in-house funded development effort, estimated a minimum cost of \$43 to \$65/m² (\$4 to \$6/ft²) for a 0.00254 cm (1 mil) thick honeycomb (Ref. 5). These costs were mainly material dependent and assume normal manufacturing methods. Hexcel also experienced manufacturing problems associated with the combination of the thin-film thickness (necessary to minimize material costs), film static charge, and its lack of handling strength. Bonding was also a problem, and although adhesives are available, they are too expensive and not amenable to honeycomb manufacturing techniques. Fusion bonding is a possible alternative, but again cost is a prime factor, and at this time Hexcel has no further plans to develop the FEP Teflon honeycomb system.

3.1.2 Combined FEP Teflon Honeycomb and Cover

Although four possible techniques were discussed previously (Ref. 5) for making an integral honeycomb/cover system, the only work performed during the present phase was the fabrication of a small demonstration model using some previously manufactured Hexcel FEP Teflon. In light of the difficulties experienced in the manufacture of the FEP Teflon honeycomb by both Hexcel and Norfield, it was decided that no further effort should be expended on the concept of an integral Teflon honeycomb/cover system.

3.1.3 FEP Teflon Cover

Based upon its excellent optical characteristics, FEP Teflon was considered a likely candidate as a glazing material. As discussed previously (Ref. 4) in order to improve dimensional stability and strength to the glazing, some form of sheet reinforcement

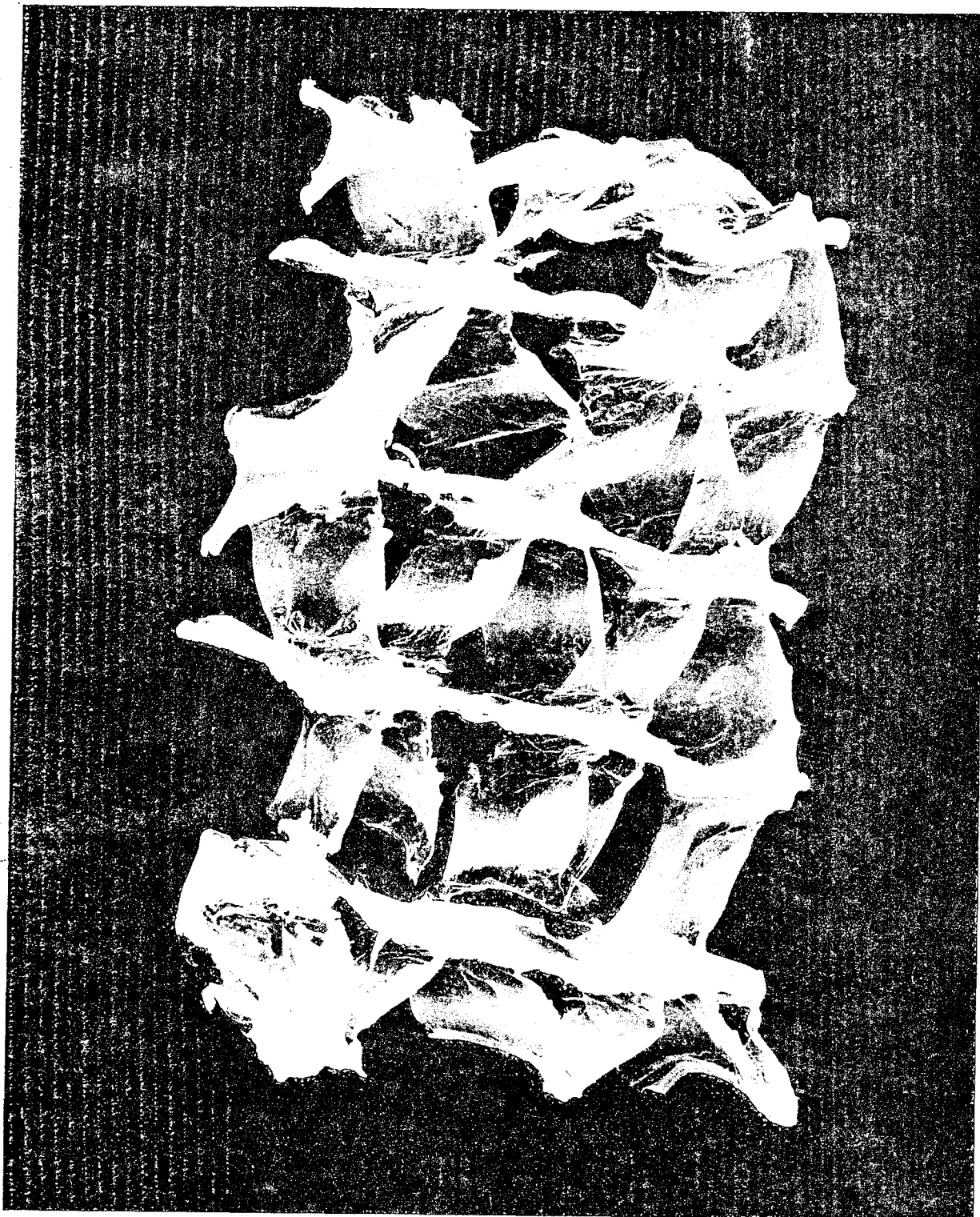


Fig. 3-1 Norfield Corp. FEP Teflon Honeycomb Sample

would have to be employed. The following companies showed interest and capability in the manufacturing of a reinforced Teflon cover:

- Orcon Corporation, Union City, California
- Lamart Corporation, Clifton, New Jersey
- Schjeldahl Corporation, Norfield, Minnesota

At this time only Orcon Corporation was contracted to provide a reinforced FEP Teflon cover to the Lockheed specifications. The finished Teflon cover was made using techniques similar to those used to manufacture the Orcon Solar Window[®], which uses a Tedlar substrate and is presently being used by some solar collector manufacturers. Figure 3-2 shows a section of the Orcon Teflon dacron reinforced cover. The dacron provides the necessary dimensional stability at little cost while strengthwise the chance of ripping is reduced considerably. The Orcon samples made and tested to date include:

- 1-mil Type A FEP Teflon/1000 Denier Dacron
- 1-mil Type C FEP Teflon/1000 Denier Dacron

The dacron in both cases was adhesively attached with a 4.08 cm spacing pattern. The price for a large quantity (greater than 10,000 ft²) was estimated at \$0.54/ft² for a 1-mil film thickness and \$0.34/ft² for a 1/2-mil film thickness (Ref. 6).

Basic strength and optical tests were done with the reinforced Teflon cover. In a pull test the reinforced Teflon failed at 90 lb compared to 25 lb for unreinforced Teflon. The solar transmission of the mesh was measured using the Cary Model 14 Spectrophotometer with integrating sphere. The transmission was 0.85 compared to a value of 0.95 for an unreinforced Teflon sample. Since the area of the mesh is 4 percent of the Teflon's area, the reinforcing causes less than a one percent drop in the cover's solar transmission.

In the Lamart and Schjeldahl process, the dacron would be heat sealed between two sheets of Teflon and therefore would remove the need for adhesive which could possibly undergo degradation after long-term exposure to the environment.

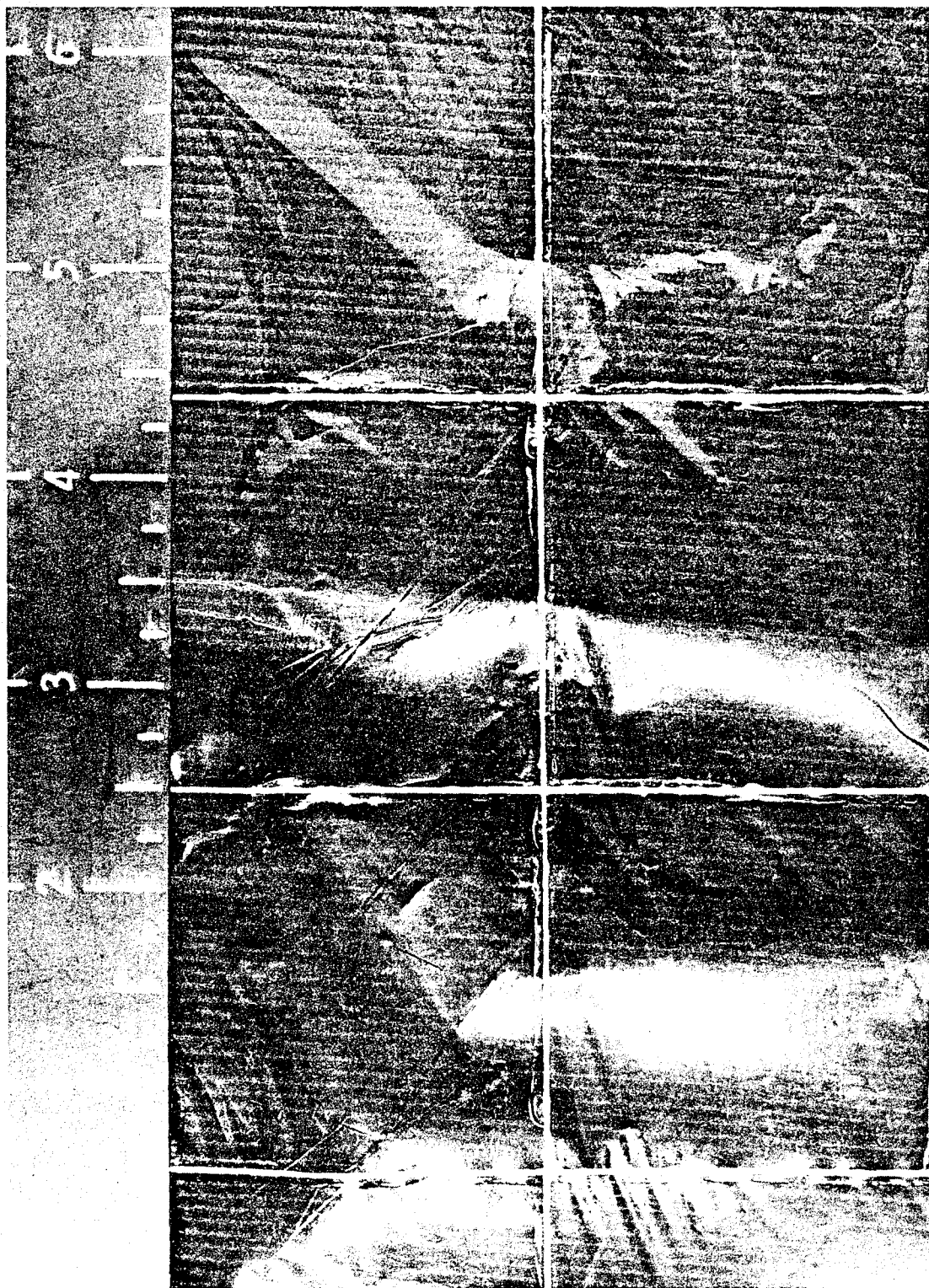


Fig. 3-2 Orcon Corp. Teflon Dacron Reinforced Cover Material

3.2 OPTIMIZATION OF LOW-TEMPERATURE PLASTIC HONEYCOMB

The objective of this task was to optimize the configuration of low-cost, low-temperature plastic honeycombs and also investigate alternative methods of fabrication in the hope of reducing manufacturing costs.

Work performed to date in Phase I (Ref. 3) and Phase II (Ref. 4) of this program showed that only Lexan and Mylar as low-temperature plastics exhibited the required properties for honeycomb manufacture. They are both relatively inexpensive, can operate at temperatures up to 137°C (278°F) and possess the desired optical characteristics.

Concerning their long-term stability, recent tests performed by General Electric (Ref. 7) have indicated that with the addition of a UV inhibitor Lexan has been shown to be UV stable. However, recent tests (Ref. 8) have indicated that many plastic materials have a lifetime expectancy of less than 15 yr in typical terrestrial environments. Mylar and Lexan, however, are among the more stable materials and are therefore considered from the points of view of stability and cost as the best candidates for honeycombs.

In this task, a survey was made of all honeycomb manufacturers to determine whether honeycomb configurations other than hexagonal are produced and, if so, their likelihood of improving collector performance and cost effectiveness. The survey showed that no other honeycomb patterns other than hexagonal were suitable for use in solar collectors. A conical cell configuration presently made by Norfield, in which the cells overlap, exhibited large solar transmission losses through the honeycomb. A rectangular cell structure appears to be a promising design as well as a material saver but at this time neither Hexcel or Norfield is interested in making such a cell configuration.

3.2.1 Honeycomb Fabrication Techniques

The methods of honeycomb fabrication as used by Hexcel and Norfield were described in detail during Phase I (Ref. 3) and Phase II (Ref. 4) of the present program. Samples

of Mylar and Lexan were received from Hexcel while only Lexan honeycomb was produced by the Norfield process. Figure 3-3 shows typical sections of the Hexcel Mylar and Lexan honeycombs used in the test program while the quality difference between the Norfield and Hexcel processes is amply demonstrated by Fig. 3-4 in which Lexan honeycombs produced by both processes are shown.

Based upon the honeycomb optimization studies performed earlier in the program, the following samples were procured from the Hexcel Corporation for detailed testing in the Lockheed Solar Test Facility.

Mylar: (i)	Film thickness	=	0.00254 cm (1 mil)
	Cell diameter (D)	=	0.953 cm (3/8 in.)
	Cell length (L)	=	5 cm (2 in.)

Mylar: (ii)	Film thickness	=	0.00254 cm (1 mil)
	Cell diameter (D)	=	0.4 cm (0.16 in.)
	Cell length (L)	=	3.56 cm (1.4 in.)

Lexan: (i)	Film thickness	=	0.00762 cm (3 mil)
	Cell diameter (D)	=	0.953 cm (3/8 in.)
	Cell length (L)	=	4.76 cm (1.875 in.)

In the case of the Norfield Corporation, the commercially available Lexan flat-top Norcore sheets had a cell diameter of 1.91 cm (3/8 in.) on 2.54-cm (1-in.) centers, yielding a honeycomb system with a hexagonal cell geometry too large for optimum convection suppression. The Lexan samples received (1 ft²) for testing were produced on a research die to provide 1.27-cm (0.5-in.)-diameter cells with a length of 4.76 cm (1.875 in.) and pieced together to cover the total collector area (4 ft. x 8 ft.)

3.3 HONEYCOMB/COVER COLLECTOR TESTING

In this task, the performance of transparent plastic honeycomb flat-plate collectors was determined in an effort to evaluate the effect of the plastic honeycombs on the

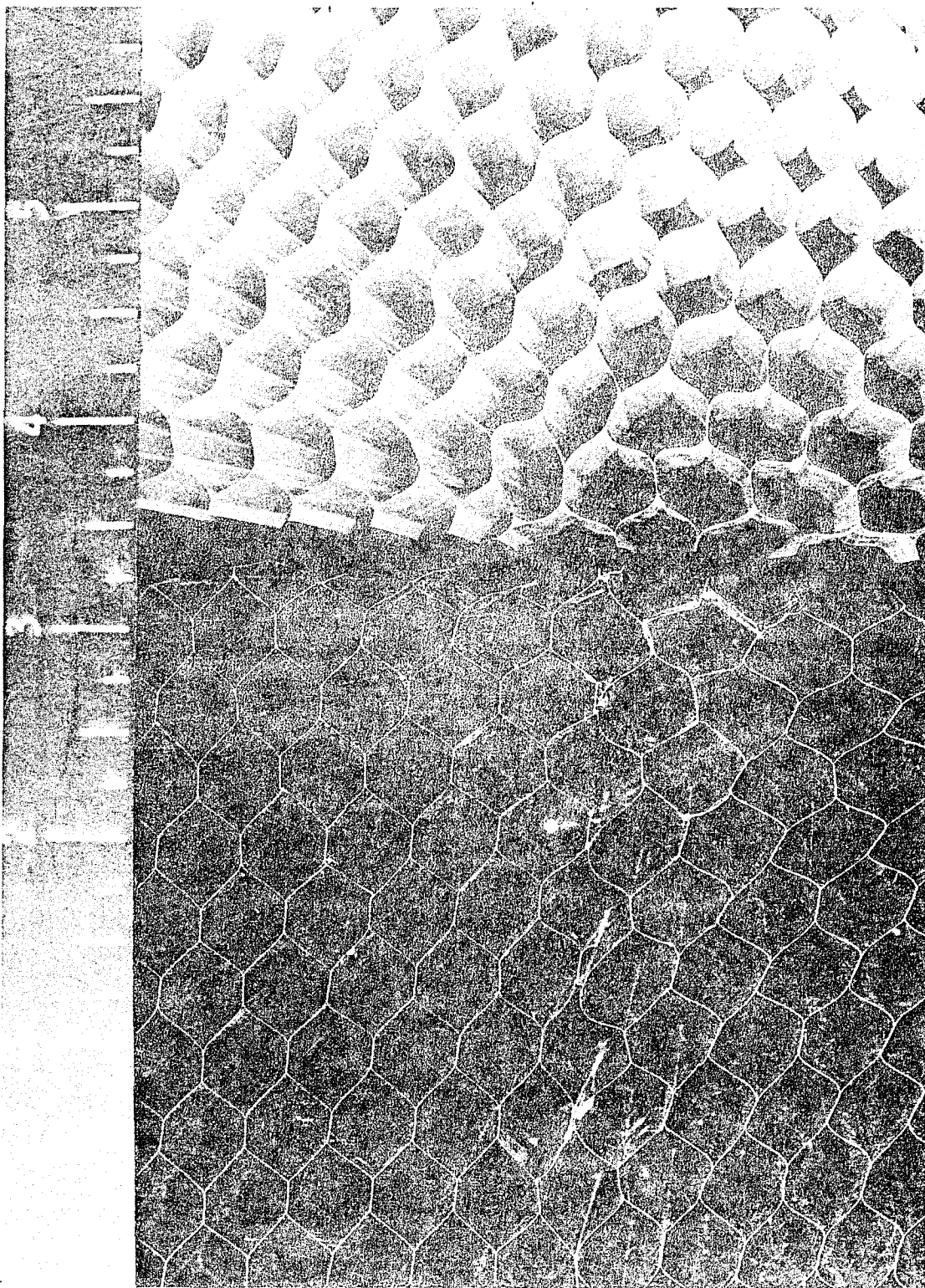
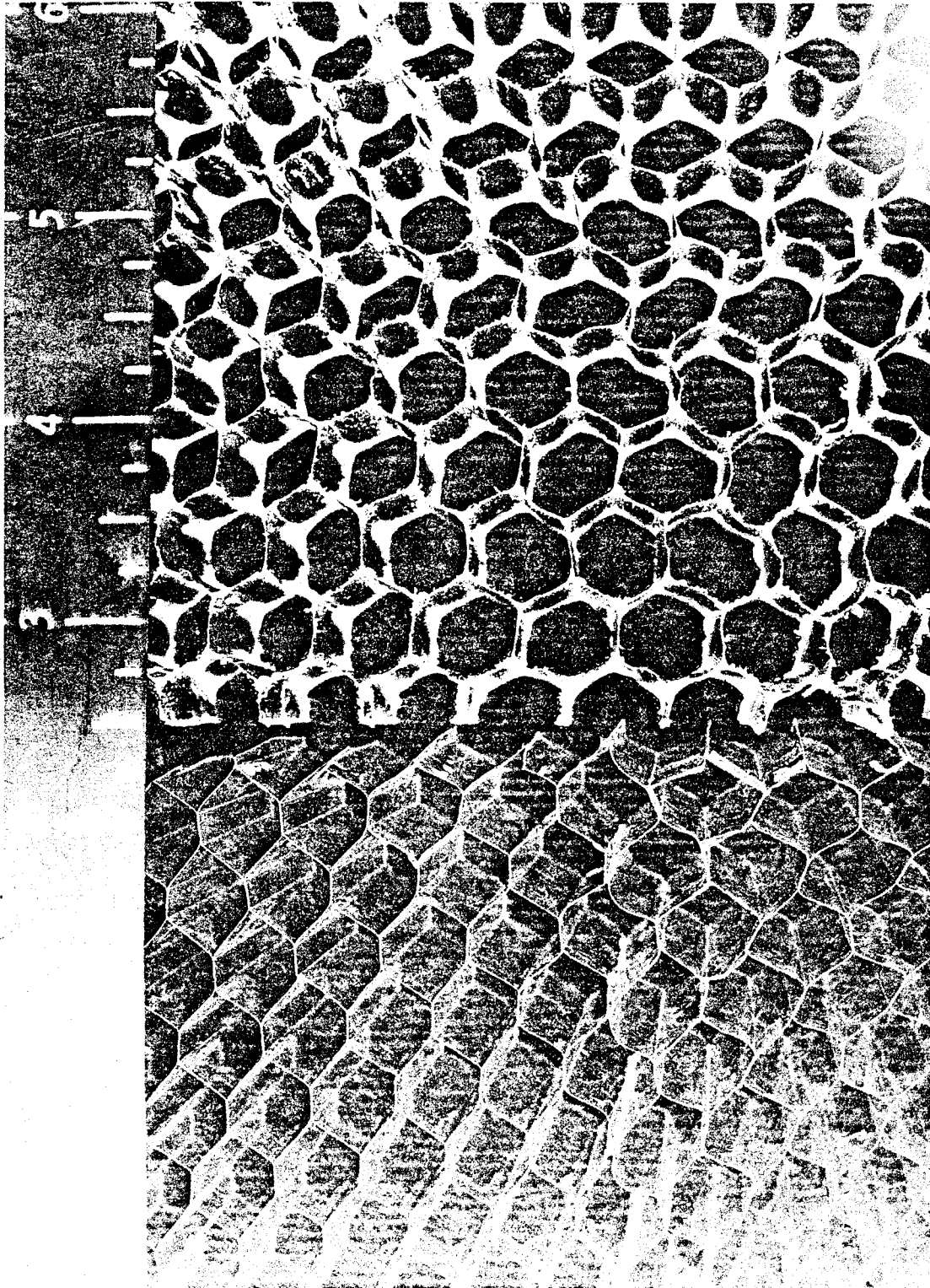


Fig. 3-3 Hexcel Corp. Mylar and Lexan Honeycomb Material -- Expanded Core Process



HEXCEL
(a)

NORFIELD
(b)

Fig. 3-4 Lexan Honeycomb Samples Manufactured by (a) Hexcel Expanded Core Process, (b) Norfield

overall collector performance. To achieve this goal, commercially available off-the-shelf collectors and LMSC-built laboratory models were tested in accordance with procedures recommended by NBSIR 74-635 (Ref. 9) under ambient weather conditions in the Lockheed Solar Collector Test Facility established for this purpose.

Performance data were obtained over a temperature range from ambient to 120°C (250°F) over a range of solar incident angles and tilt angles and over a range of weather conditions. Testing was conducted simultaneously on honeycomb and non-honeycomb systems to obtain a direct comparison of performance.

Collector performance was measured in terms of instantaneous and diurnal efficiencies and in terms of environmental stability of collector materials. The collector efficiency was determined by the amount of energy removed by the collector fluid compared to the total amount of terrestrial solar energy incident on the collector. The incident solar energy was measured using a pyranometer. The useful energy removed by the fluid was computed from the fluid properties, the mass-flow rate, and the temperature rise of the fluid as it traversed the collector. Environmental stability of the honeycomb materials was determined during this program by noting any visible changes in shape during elevated temperature operation.

3.3.1 Collector Configuration and Test Procedure

To evaluate the performance characteristics of the Lexan and Mylar honeycombs when incorporated into a flat-plate collector, two types of collectors were used in the test program. A Chamberlain collector (Ref. 10) of the type used in the NBS Round Robin Tests (Ref. 11), incorporating a selective black absorber coating, was tested with and without honeycomb. Specifically, the collector was 2.09 m × 0.96 m (6.86 ft × 3.14 ft) with a black chrome selective coating ($\alpha_s/\epsilon = 0.95/0.10$) on a steel absorber plate and a single Fourco glass cover. A Lockheed-designed and fabricated collector was used to evaluate the performance of the honeycomb with a flat black coating. The coating was 3M Black Velvet ($\alpha_s/\epsilon = 0.98/0.90$) on a Roll-Bond aluminum absorber plate 0.43 m × 1.27 m (1.4 ft × 4.17 ft) with a single cover of Sunadex glass ($\tau_g = 0.91$).

The testing was performed in accordance with NBS procedures at the Lockheed Solar Collector Test Facility, Palo Alto, California, with the equipment and in the manner described previously (Ref. 3). For each collector configuration, the performance was obtained for a range of inlet fluid temperatures from near ambient up to 120°C (247°F) with up to four collectors being tested simultaneously. Both instantaneous and diurnal performance were measured. Shown in Fig. 3-5 is the test rack setup while Fig. 3-6 shows one of the Lockheed-designed flat black collectors without honeycomb. Before honeycomb testing started, the three Lockheed collectors were tested simultaneously over a wide range of temperatures, and the results indicated no discernible difference in the performance. At the completion of all honeycomb collector testing, the honeycombs were removed from the collectors and the collectors were retested to establish that no performance changes had occurred.

For each collector system tested, both instantaneous and diurnal results are presented. In the case of the instantaneous results, the efficiency is reported as a function of the difference between the average fluid and air temperature divided by the incident solar radiation, i. e. , $\Delta T/I$. The curve fit is not a straight line but is drawn to emphasize the non-linear decrease in efficiency at temperatures above 90°C (194°F) where the radiation heat transfer, a fourth-order temperature-dependent term, is important. With the diurnal results the useful energy collected per unit area of collector was considered to be the pertinent parameter. The results are presented for an inlet temperature close to 90°C (194°F), the temperature necessary for efficient operation of solar-powered air conditioning systems.

3.3.2 Honeycomb/Flat Black Collector Systems

Lexan Honeycomb (Hexcel). Based upon the analytical studies performed in Phase I, a Lexan honeycomb structure with an aspect ratio (L/D) of five was determined to be the optimum configuration for maximum collector efficiency. The honeycomb tested was 0.00762 cm (3 mil) thick (T) with a cell diameter (D) of 0.962 cm (3/8 in.) and cell length (L) of 4.76 cm (1-7/8 in.). Figure 3-7 shows the Lockheed-designed collectors with honeycomb in place. The glass covers of the collectors have been removed to give a better view of the honeycomb.

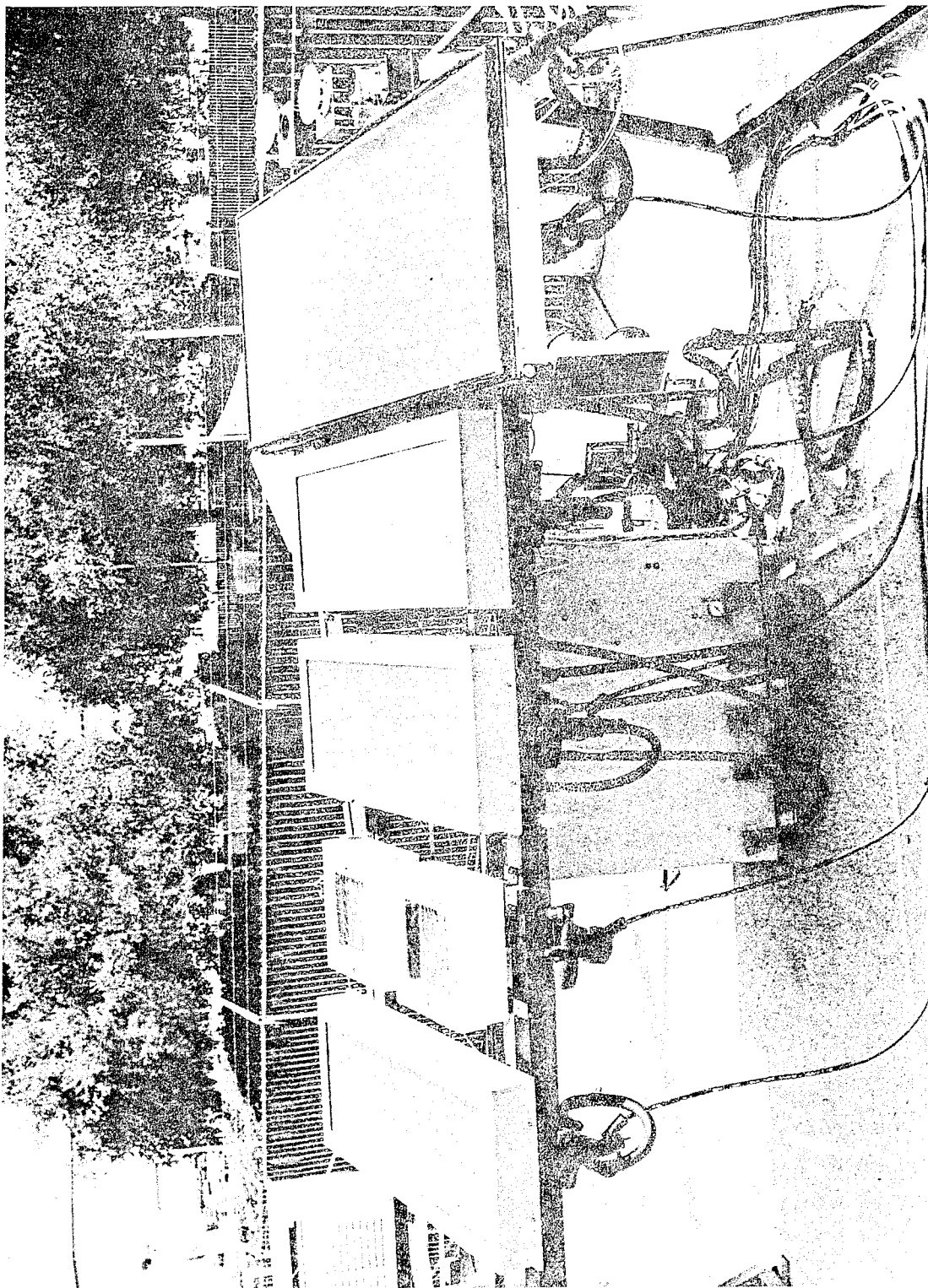


Fig. 3-5 Lockheed Test Rack Assembly

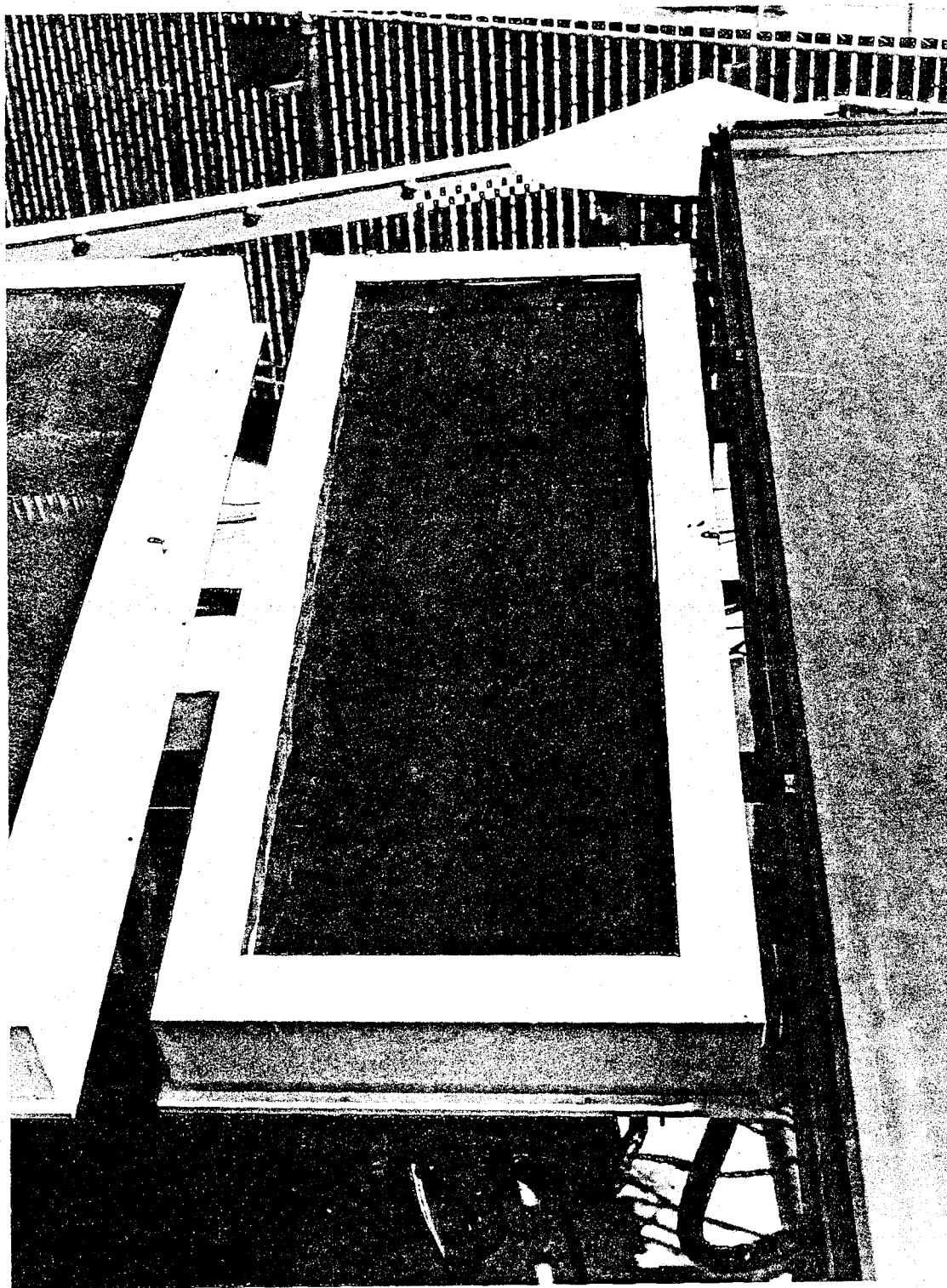


Fig. 3-6 Lockheed Built Flat Black Solar Collector

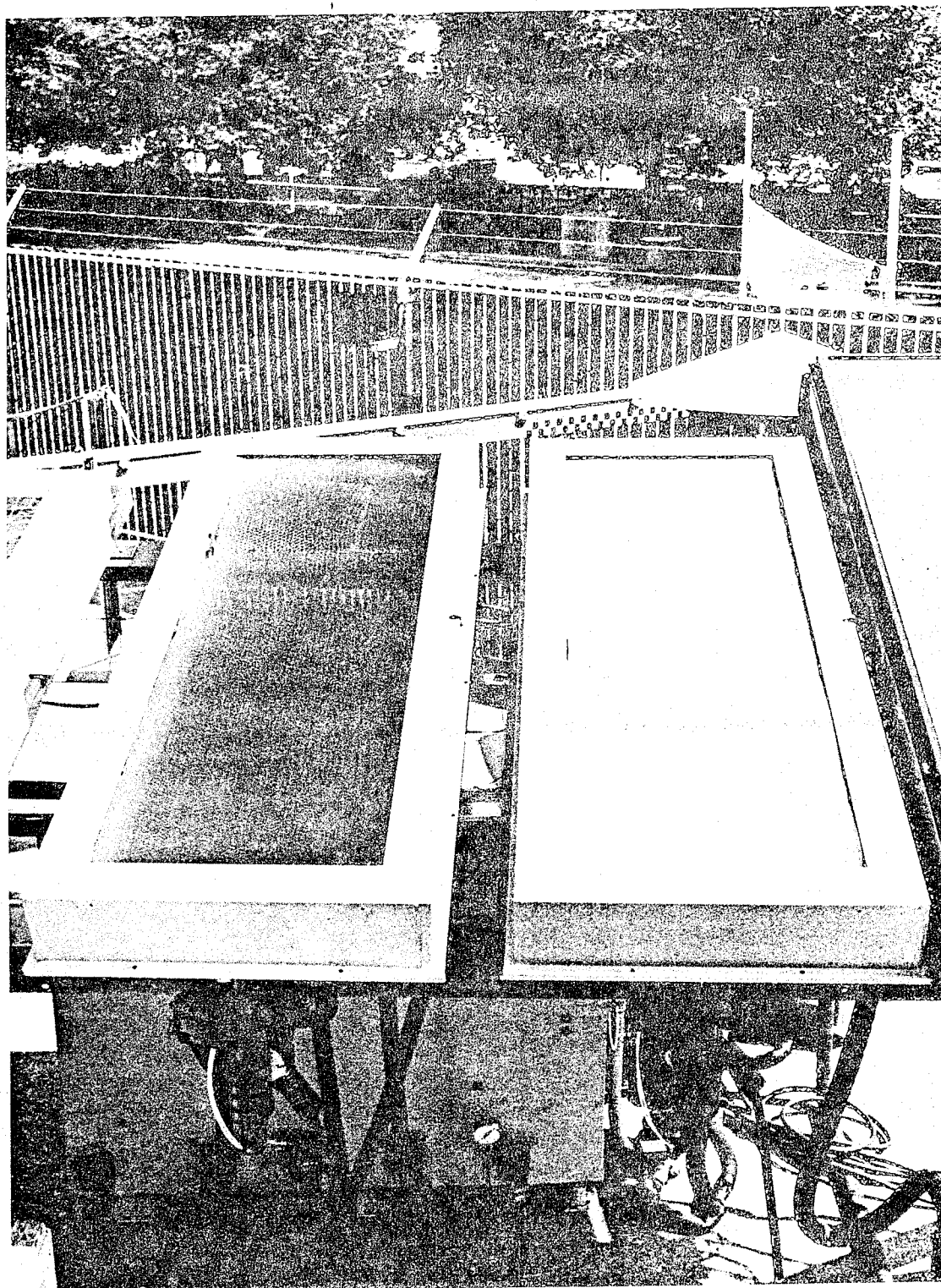


Fig. 3-7 Lockheed Built Flat Black Collector With Lexan Honeycomb

The improved performance of the flat black collector due to the Lexan honeycomb is shown in Fig. 3-8. When the collector temperature is close to ambient, the performance of both collectors, one with and the other without honeycomb, is essentially the same. Since the heat losses at the low temperature differences are small, these results verify that the solar transmission loss through the honeycomb is small. As the collector temperature increases, the honeycomb collector performance is superior to the nonhoneycomb collector. This superiority indicates the effect of the honeycomb on radiation losses and convection suppression.

The diurnal results for the same two collectors are shown in Fig. 3-9 from which it can be seen that the honeycomb collector is more efficient throughout the day and actually collects useful energy over a longer time span (~ 2 hr) than the nonhoneycomb collector. The integrated energy and diurnal efficiency for the Hexcel Lexan honeycomb collector are listed below:

	<u>Lexan Honeycomb</u>	<u>No Honeycomb</u>
Diurnal useful energy (W-hr/m ²)	3210	1426
Diurnal efficiency	0.41	0.18

On a diurnal basis, the efficiency of the honeycomb collector decreases slower than does the efficiency of the nonhoneycomb collector; therefore, on a daily basis the honeycomb collector is even more efficient than the nonhoneycomb collector than indicated by the instantaneous results. The diurnal results also verify that the honeycomb performance does not seriously degrade at large solar incident angles.

Lexan Honeycomb (Norfield). As reported previously (Ref. 4) in this work, the Norfield honeycomb as received was approximately 7.62 in. (3 in.) thick with an integral cover attached. To test it as a honeycomb, the attached covers had to be removed and the honeycomb sections cut to the required cell length. Two methods of cutting were tried: a "cold" saw cut and a "hot-wire" melt cut. Inspection of both methods clearly showed that some loss in transmission would occur due to thickening of the cell at the cut edges, and also the edges were somewhat uneven.

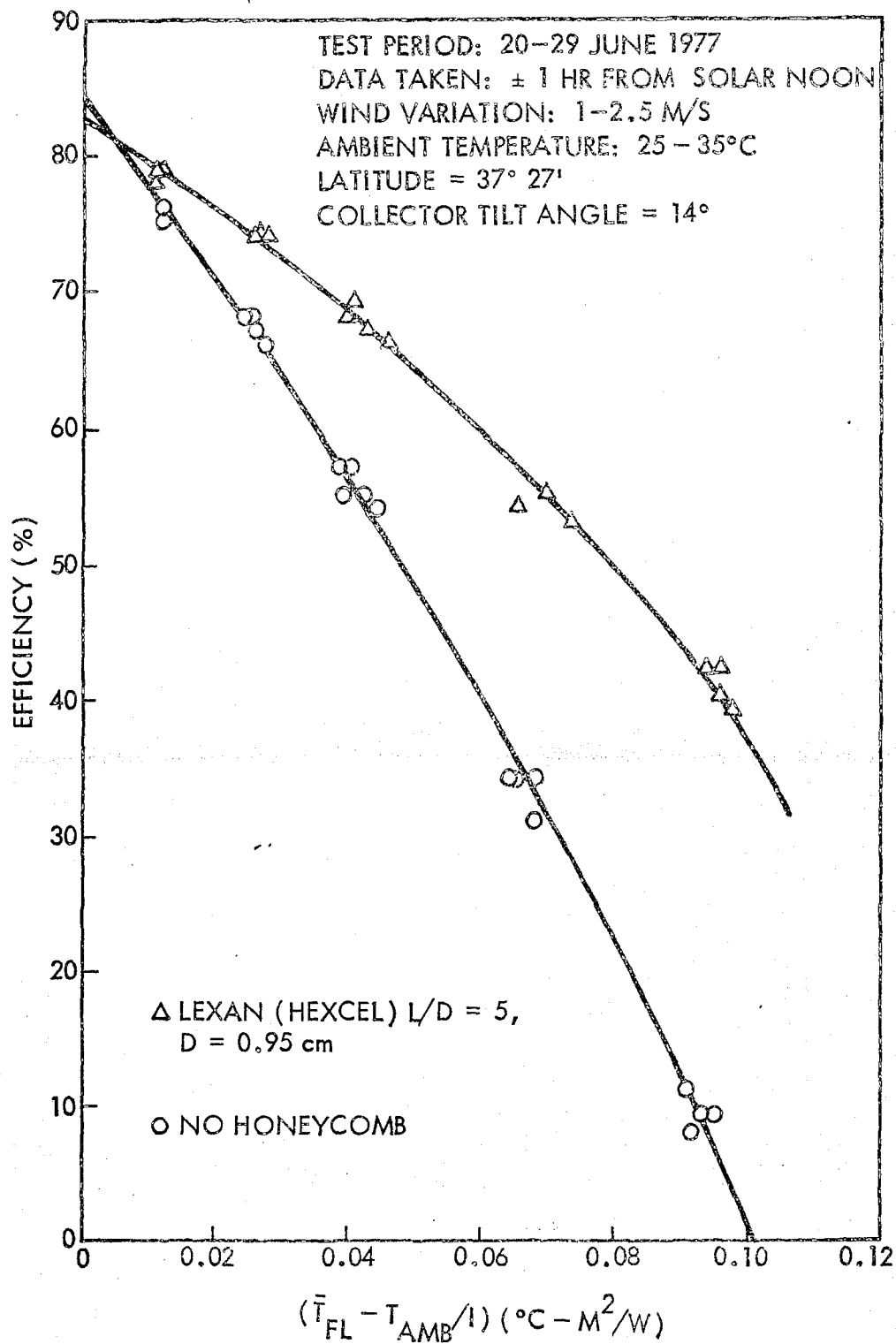


Fig. 3-8 Effect of Hexcel Lexan Honeycomb on the Performance of a Collector With a Flat Black Absorber and Glass Cover

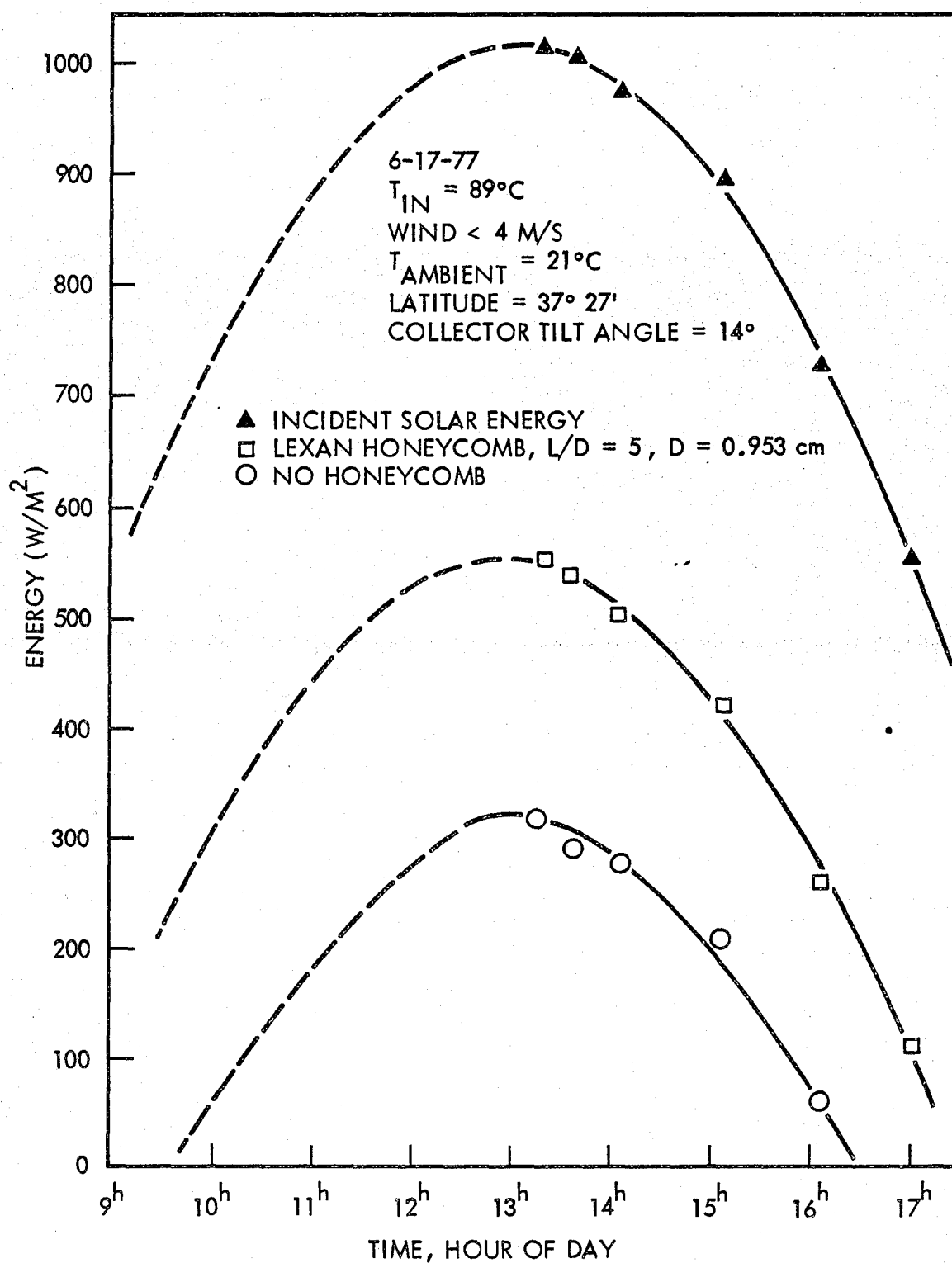


Fig. 3-9 Diurnal Performance of a Glass Covered Flat Black Collector With and Without Hexcel Lexan Honeycomb

Figure 3-10 shows the instantaneous efficiency of the collectors with and without honeycomb and also the difference in efficiency due to the method of cutting. The "cold" saw cut improved the efficiency approximately 3 percent over the "hot-wire" melt cut, substantiating the previous observations that a loss in solar transmission did occur.

As was the case with the Hexcel Lexan honeycombs, the Norfield honeycomb gave improved collector efficiency over a nonhoneycomb collector. However, the increased efficiency was less than that obtained using the Hexcel Lexan which was attributed to some extent to the difference in aspect ratio, 3.75 to 5. This difference causes the Hexcel honeycomb to be slightly more efficient since its effective emittance (ϵ_{eff}) is less than that of the Norfield honeycomb. Another pertinent effect is that at an aspect ratio of 5 convection suppression takes place, while for an aspect ratio of 3.75 a reduced amount of convection suppression occurs (Nusselt number ≈ 1.25). At low $\Delta T/I$, where heat losses are small, the difference in collector efficiency between the Hexcel and Norfield honeycombs are appreciable enough to indicate that differences in solar transmission are the major factor.

The diurnal performance for the Norfield Lexan honeycomb is shown in Fig. 3-11, where again the improved performance due to honeycomb is obvious as is the longer period of useful energy collection. These data are summarized below.

	<u>Norfield Honeycomb</u>	<u>No Honeycomb</u>	<u>Hexcel Honeycomb</u>
Diurnal useful energy (W-hr/m ²)	2190	1426	3210
Diurnal efficiency	0.28	0.18	0.41

Mylar Honeycomb (Hexcel). The optimization studies performed in Phase I (Ref. 3) showed that Mylar honeycomb was a potential low-temperature plastic worthy of detailed testing. Hexcel Corporation provided 0.00254 (1 mil) of honeycomb with cell diameter 0.953 cm (3/8 in.) and cell length 5 cm (2 in.). Figure 3-12 shows the results obtained for the instantaneous efficiency of a Mylar honeycomb as compared to a nonhoneycomb collector. The higher efficiency at the low temperatures

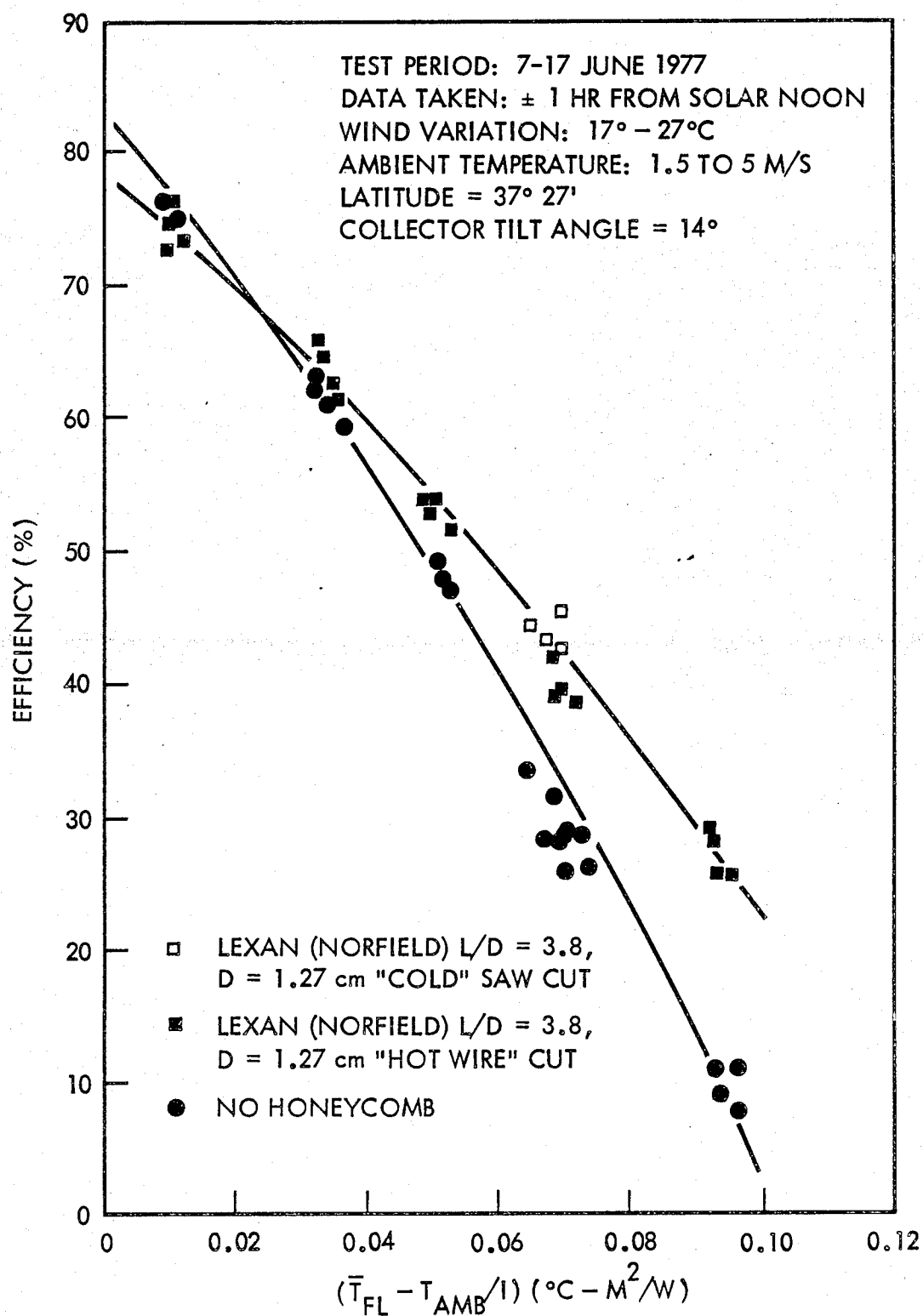


Fig. 3-10 Effect of Norfield Lexan Honeycomb on the Performance of a Collector With a Flat Black Absorber and Glass Cover

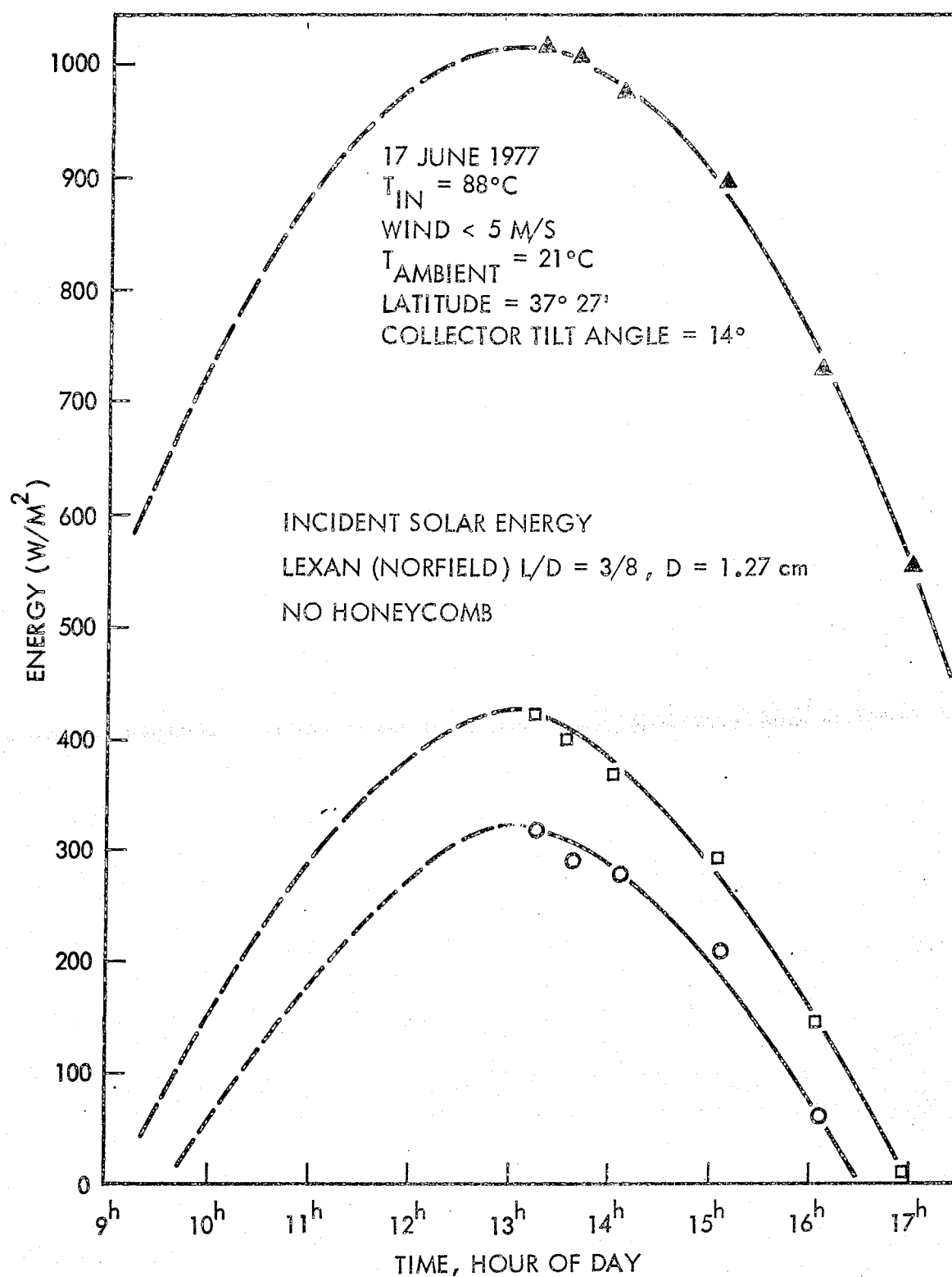


Fig. 3-11 Diurnal Performance of a Glass Covered Flat Black Collector With and Without Lexan Honeycomb Made by Norfield

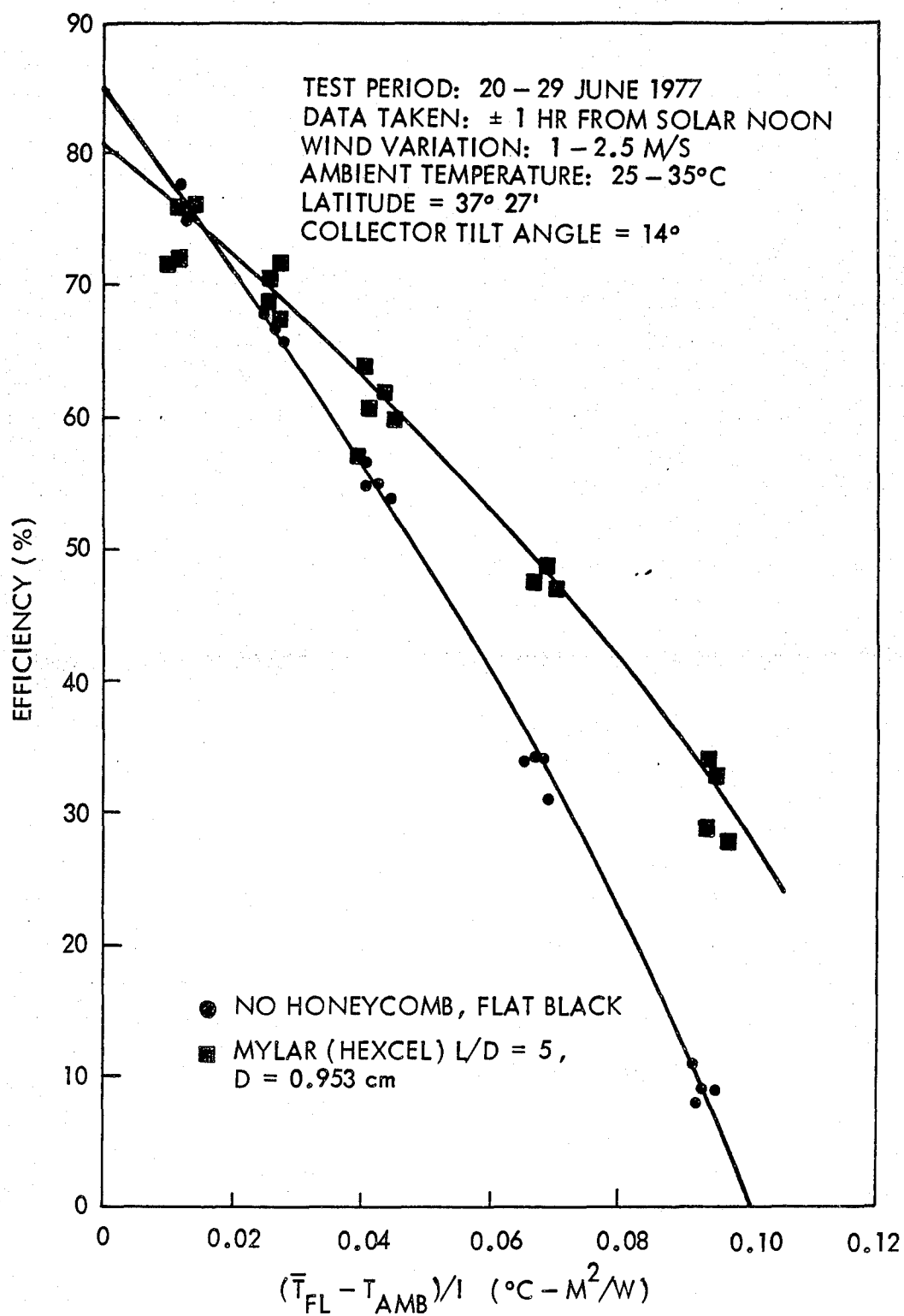


Fig. 3-12 Effect of Hexcel Mylar Honeycomb on the Performance of a Collector With a Flat Black Absorber and Glass Cover

of the nonhoneycomb collector is due to solar transmission losses through the Mylar. As the temperature increases, the honeycomb reduces the heat losses which offset the transmission losses so that the overall result is an increase in the collector efficiency with increasing temperature. With the Mylar, there was a measurable amount of data scatter, and this is suspected to be due to changes in the solar transmission of the Mylar at various solar incident angles. The diurnal performance of the collectors is given in Fig. 3-13 where at noon the Mylar honeycomb collector collected approximately 150 W/m^2 more than the nonhoneycomb collector. This difference decreased, however, as the solar incident angle changed due to a loss in the Mylar honeycomb's solar transmission. Although less efficient than a Lexan honeycomb, the Mylar collected approximately 50 percent more useful energy than the non-honeycomb collector, operating for 1 hr more during the day.

The integrated diurnal results for the Mylar honeycomb collector are tabulated below.

	<u>Mylar</u> <u>Honeycomb</u>	<u>No</u> <u>Honeycomb</u>
Diurnal useful energy (W-hr/M ²)	2570	1620
Diurnal efficiency	0.34	0.22

Comparison of Hexcel's Mylar and Lexan Honeycombs. To make a meaningful comparison between the Mylar and Lexan honeycombs, tests were run in which three identical Lockheed-designed collectors were used. The Mylar honeycomb was placed in one collector, the Lexan was placed into another, and the third collector was used as the baseline with no honeycomb. The only variable parameter was in the honeycomb wall thickness where the Mylar was 0.00254 cm (1 mil) and the Lexan 0.00762 cm (3 mil), but in both cases the convection suppression characteristics were identical.

Since the radiation and convection losses are slightly lower for Mylar than Lexan honeycomb, due to the difference in effective emittance, it was anticipated that the Mylar collector would exhibit a higher performance. This, however, was not the case as shown in Fig. 3-14, where it can be seen that the Lexan collector was more efficient than the Mylar. This improved performance was found to be independent of temperature and supported the claim that the solar transmission was the critical parameter to honeycomb collector performance.

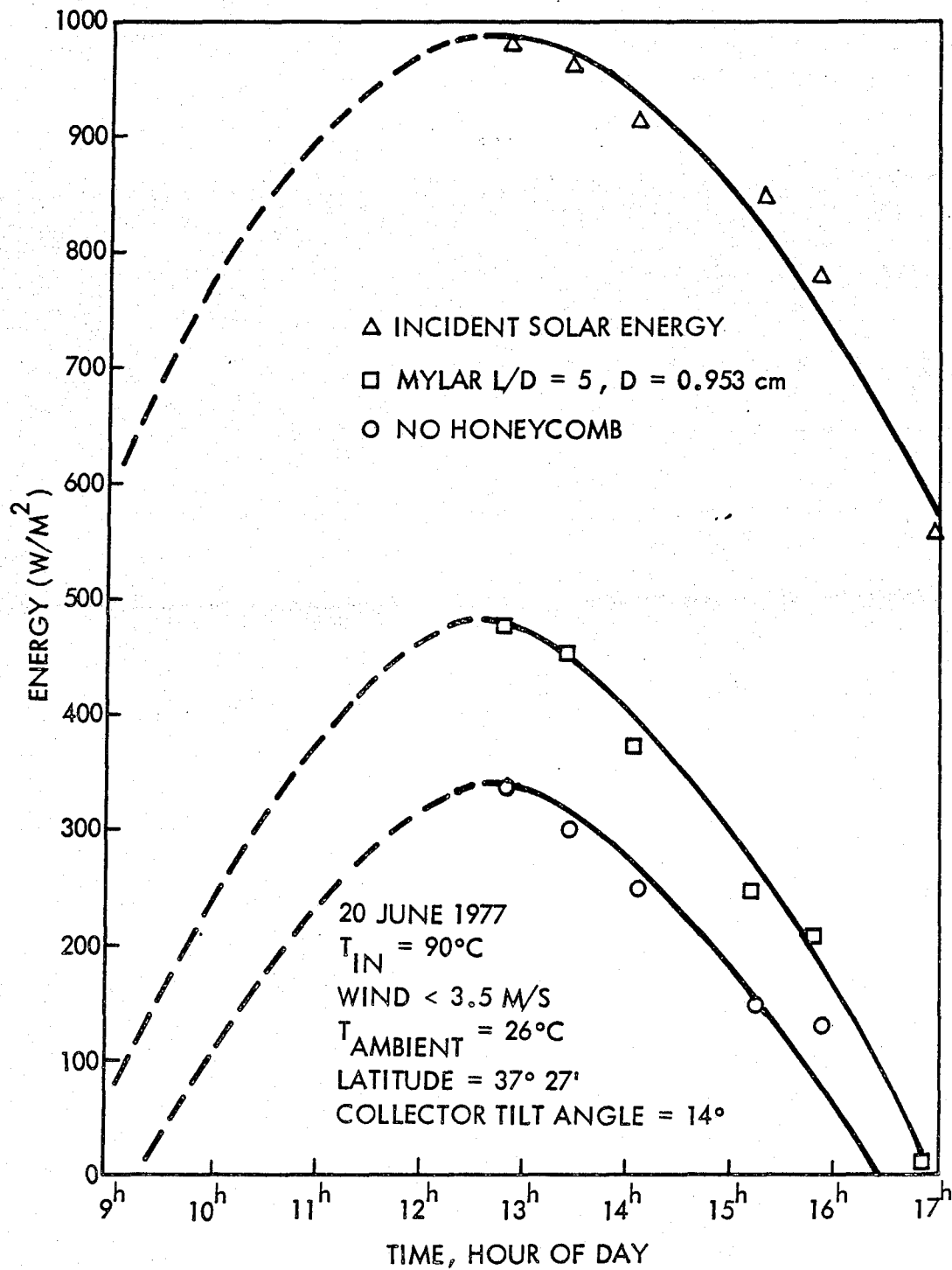


Fig. 3-13 Diurnal Performance of Glass Covered Flat Black Collectors With and Without Mylar Honeycomb

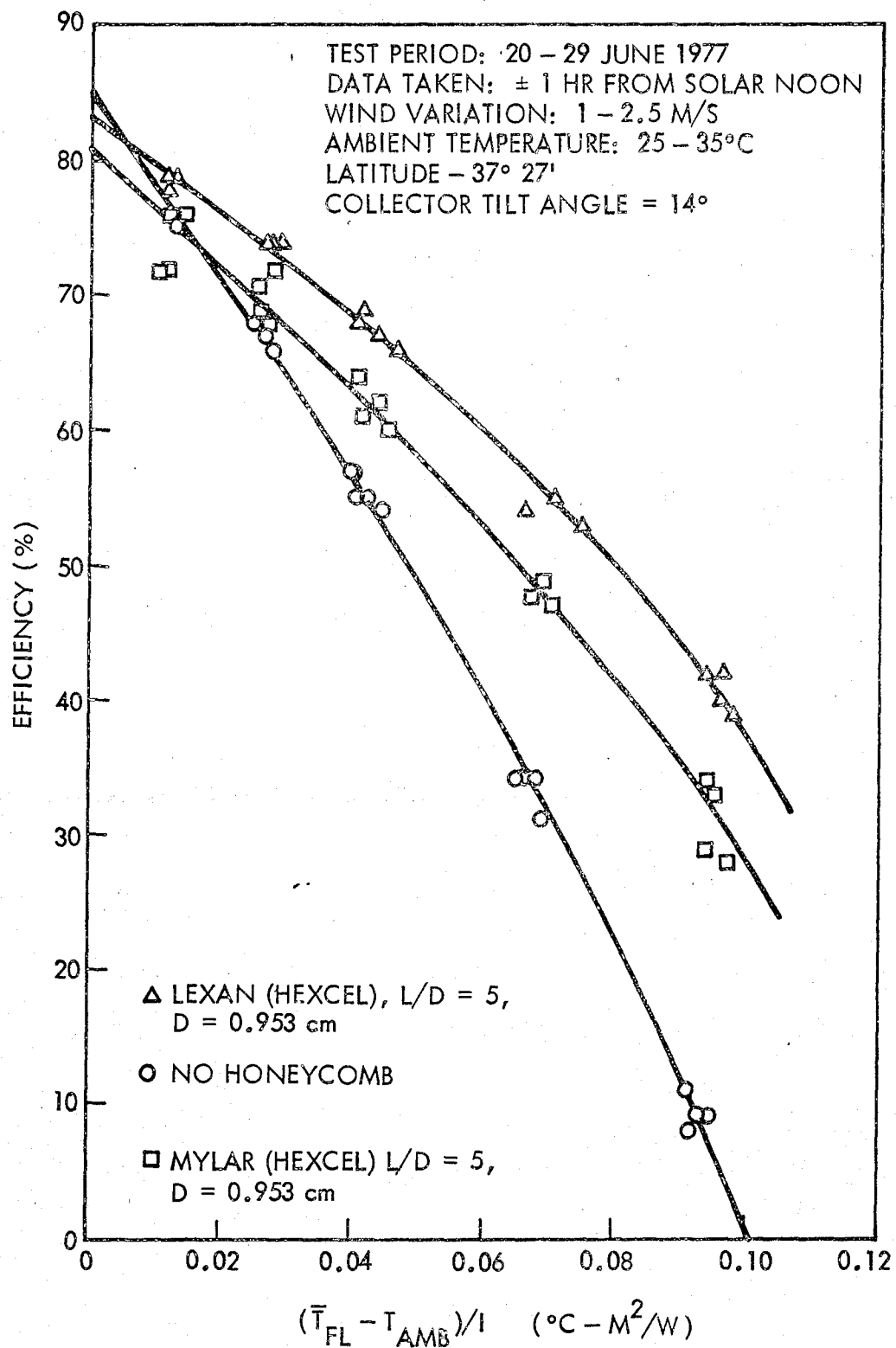


Fig. 3-14 Difference in Performance of a Flat Black/Glass Covered Collector With Hexcel's Lexan and Mylar Honeycomb

This is verified by the fact that the difference in performance is essentially independent of temperature as would be the case if the solar transmission were the critical parameter.

Comparison of the diurnal performance of the two materials is given in Fig. 3-15, while the integrated results are tabulated below.

	<u>Lexan Honeycomb</u>	<u>Mylar Honeycomb</u>	<u>No Honeycomb</u>
Diurnal useful energy (W-hr/m ²)	3140	2570	1620
Diurnal efficiency	0.46	0.34	0.22

On a daily basis, the Lexan honeycomb collector was 12 percent more efficient than the Mylar honeycomb collector, while the difference in instantaneous efficiency, measured at solar incident angles less than 30 deg, was approximately 7 percent at 90°C ($\Delta T/I = 0.07^\circ\text{C} - \text{M}^2/\text{W}$). These results further verified the decrease in solar transmission with solar incident angle for the Mylar honeycomb.

3.3.3 Honeycomb/Selective Black Collector System

To evaluate the advantages of incorporating a honeycomb into a collector system, it was necessary to compare the performance of a selective black absorber with and without honeycomb. The Chamberlain collector described in section 3.3.1 was used in the test series along with the Hexcel Mylar and Norfield Lexan honeycombs. Unfortunately, no Hexcel Lexan was available for comparison in these tests since the sample used in the previous tests with the Lockheed collectors was too small to cover the entire absorber surface of the Chamberlain collector.

Mylar Honeycomb (Hexcel). The instantaneous efficiency of two identical Chamberlain collectors, one with a Mylar honeycomb and the other without, is shown in Fig. 3-16 for solar incident angles less than 30 deg (i.e., near solar noon). At the lower temperatures, the nonhoneycomb collector is more efficient because of the Mylar honeycomb absorbing an appreciable amount of the sun's energy. As the temperature increases

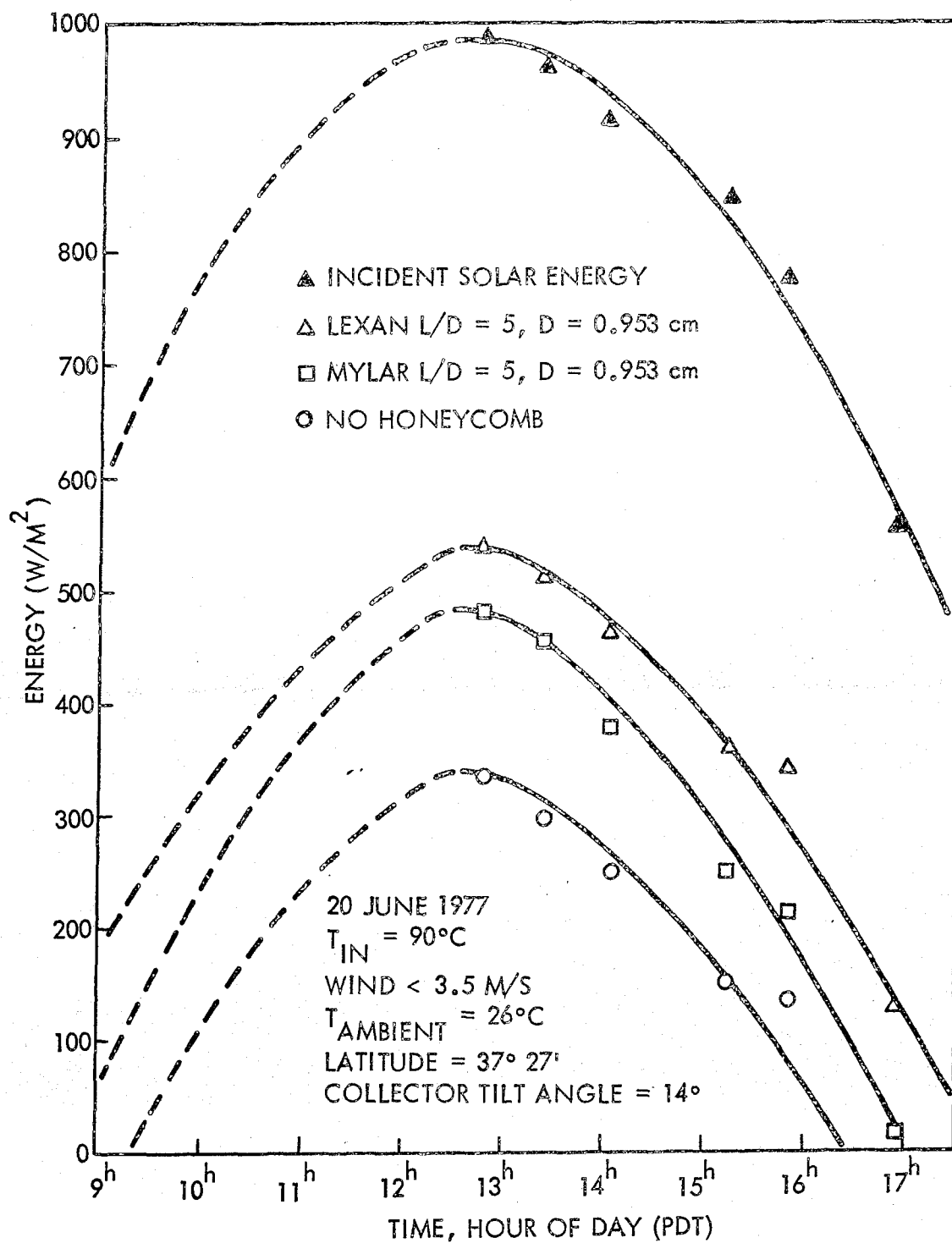


Fig. 3-15 Comparison of Diurnal Performance Between Glass Covered, Flat Black Collector With Hexcel Lexan and Mylar Honeycombs

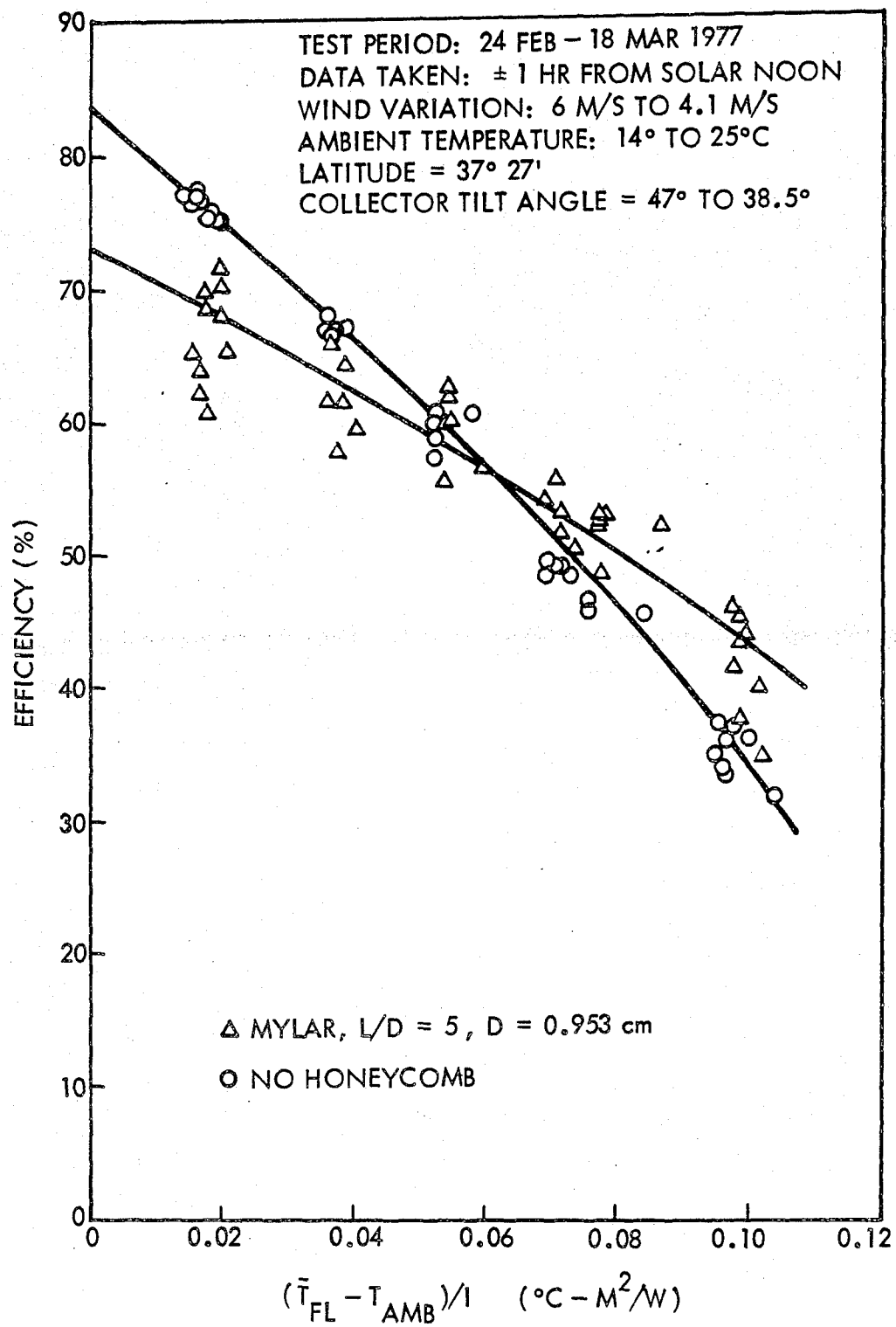


Fig. 3-16 Effect of Mylar Honeycomb on the Performance of a Glass Covered, Selective Black Collector

and the heat losses due to convection increase, the efficiency of the honeycomb collector increases over the nonhoneycomb collector due to suppression of the convective heat losses by the honeycomb.

In considering the diurnal performance of two collectors (Fig. 3-17), it was concluded that while the Mylar collector is more efficient near solar noon, there is no appreciable difference in the performance of the two collectors at solar incident angles greater than 15 deg. The daily integrated results are given below from which it can be seen that only 4 percent more useful energy was collected using the honeycomb.

	<u>Mylar Honeycomb</u>	<u>No Honeycomb</u>
Diurnal useful energy (W-hr/m ²)	2380	2572
Diurnal efficiency	0.36	0.32

Lexan Honeycomb (Norfield). In discussing the performance of the Norfield and Hexcel Lexan honeycomb systems in section 3.3.2, it was pointed out that the disparity in results with the flat black absorber was due to the difference in the transmission characteristics of the two materials. This difference was attributed to the Norfield manufacturing process and the sample cutting techniques. In the light of these results, it was expected that using the Norfield Lexan with the Chamberlain collector would show little or no improvement in collector performance over a nonhoneycomb Chamberlain collector. Figure 3-18 confirmed these expectations in that at high operating temperatures both collectors exhibited the same efficiency, while at the lower temperatures, the nonhoneycomb collector was more efficient. These differences are explained by the fact that transmission properties are the critical parameter at the lower temperatures; at higher temperatures, on the other hand, the critical parameter is high heat loss which is minimized by the honeycomb. The results are consistent with those obtained for the flat black absorber system and emphasize the need to perform similar testing on a Hexcel Lexan/selective black absorber system.

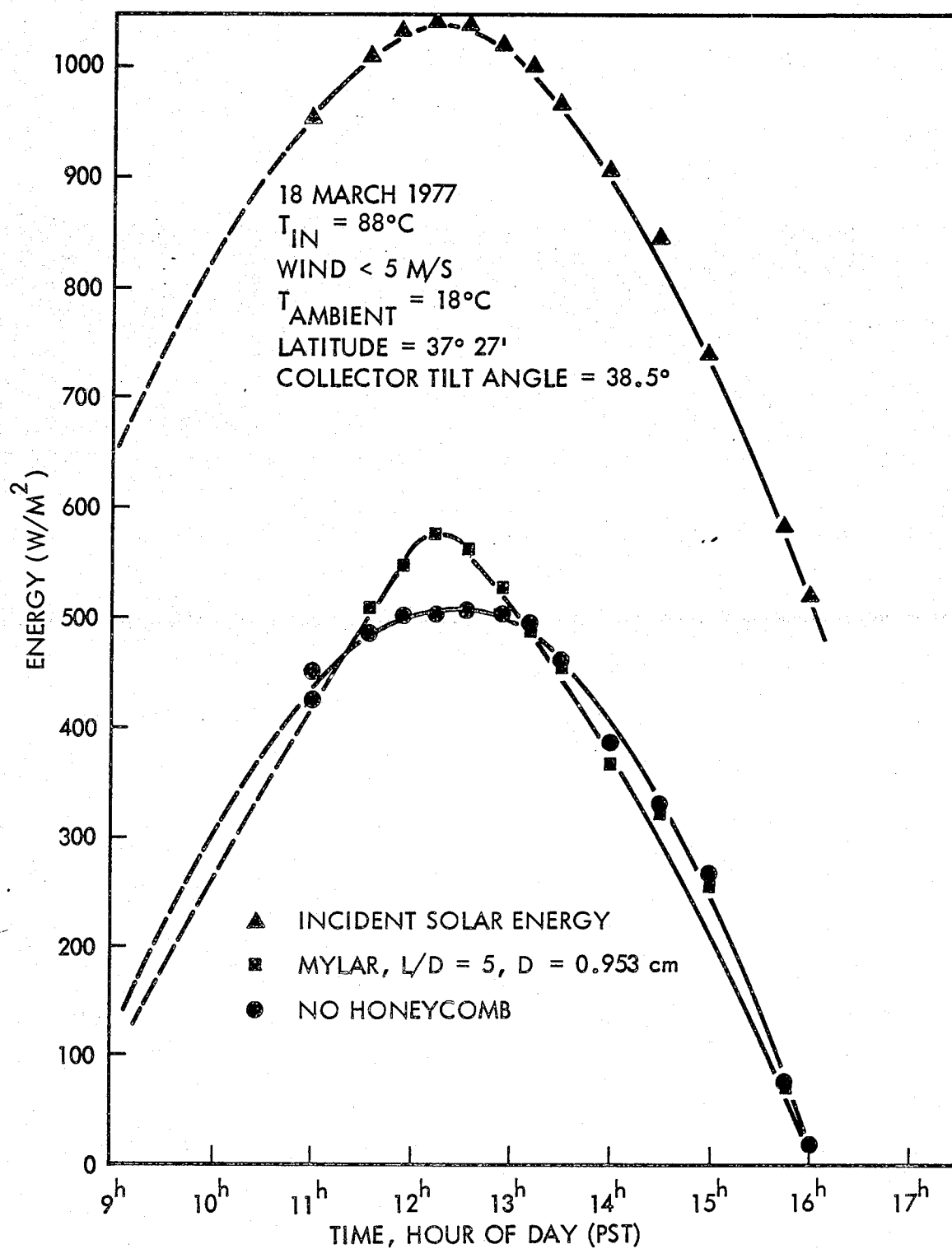


Fig. 3-17 Diurnal Performance of Mylar Honeycomb, Glass Cover, Selective Black Collector

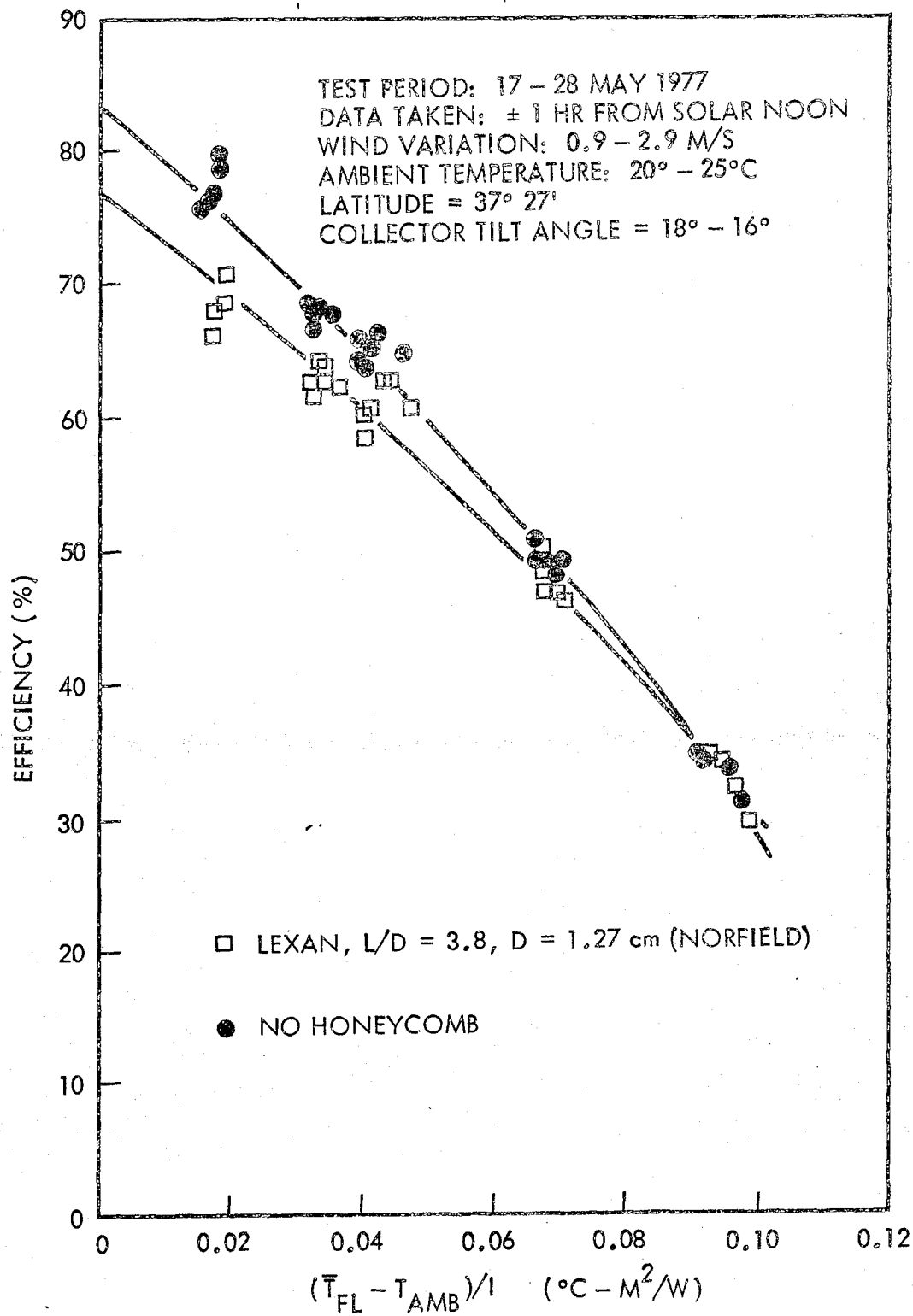


Fig. 3-18 Effect of Norfield Lexan Honeycomb on the Performance of a Glass Covered, Selective Black Collector

3.3.4 Comparative Collector Testing

Figures 3-19, 3-20, and 3-21 show the results of a test series in which four collectors were tested simultaneously, thereby ensuring constant test conditions. The systems tested were:

- Flat black/no-honeycomb
- Flat black/Hexcel Mylar honeycomb (L/D = 5)
- Flat black/Hexcel Lexan honeycomb (L/D = 5)
- A selective black/no honeycomb (i.e., Chamberlain collector)

Over the temperature range tested, the Lexan honeycomb/flat black system is the most efficient, but the results indicate that at higher $\Delta T/I$ than was tested, the efficiency of the selective black/no honeycomb collector will approach the Lexan honeycomb/flat black design. The diurnal results are listed below for inlet collector temperatures of 88°C and 115°C.

System Tested	Diurnal Useful Energy (W-hr/m ²)		Diurnal Efficiency	
	Inlet Temperature			
	88°C	115°C	88°C	115°C
Flat Black/No Honeycomb	1620	320	0.22	0.04
Flat Black/Lexan Honeycomb	3140	2040	0.46	0.27
Flat Black/Mylar Honeycomb	2570	—	0.34	—
Selective Black/No Honeycomb	2720	1760	0.36	0.23

In considering the four systems tested, it is clear that at low temperatures the flat black/Lexan honeycomb collector is slightly more efficient. At intermediate temperatures, where convection losses dominate the overall performance, the flat black/Lexan honeycomb collector is appreciably more efficient. At relatively high temperatures (> 150°C), the selective black collector tends to become the most efficient.

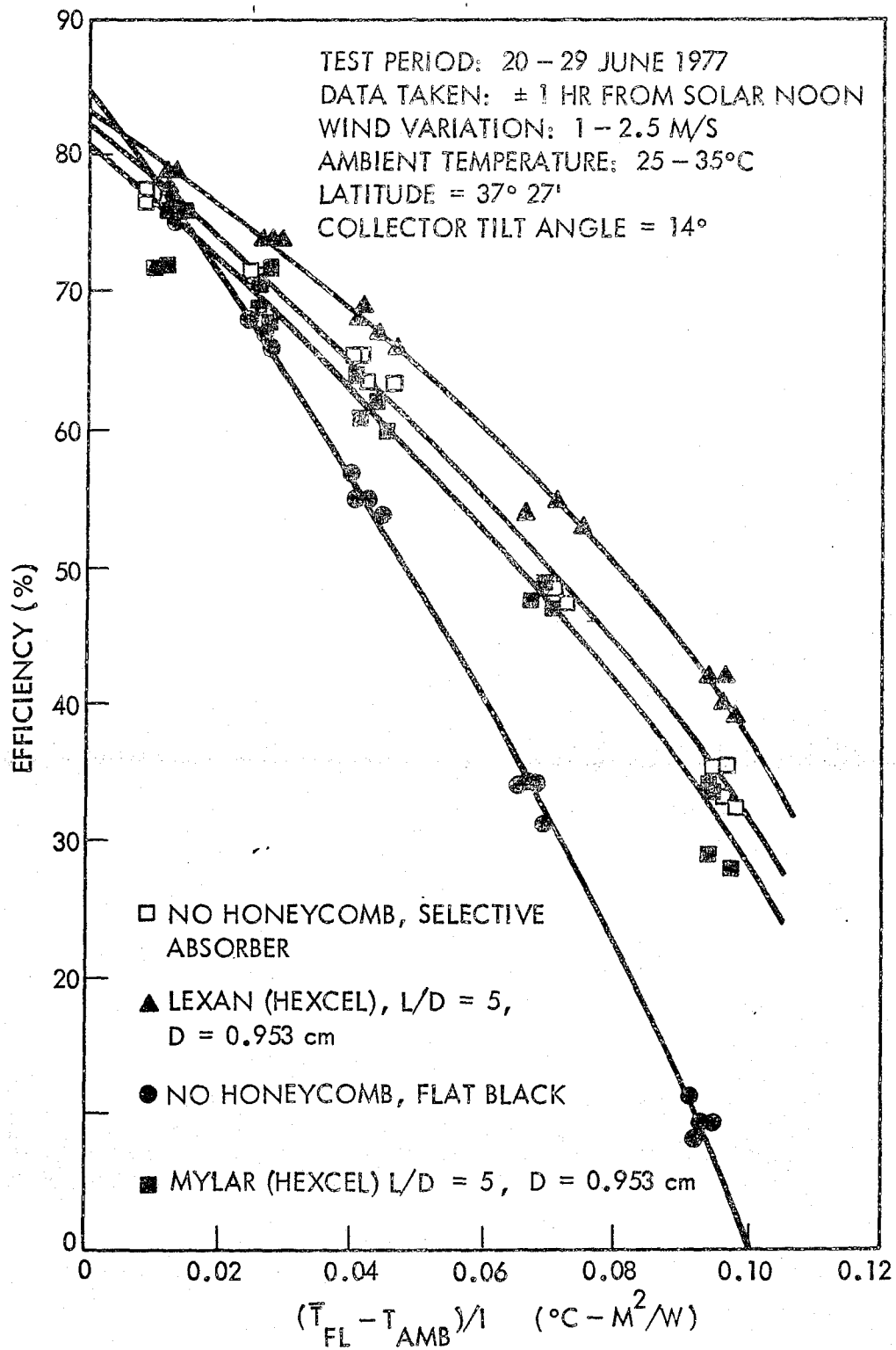


Fig. 3-19 Comparison of Efficiency Between a Glass Covered Flat Black Collector With and Without Hexcel Lexan Honeycomb and a Selective Black, No Honeycomb Collector

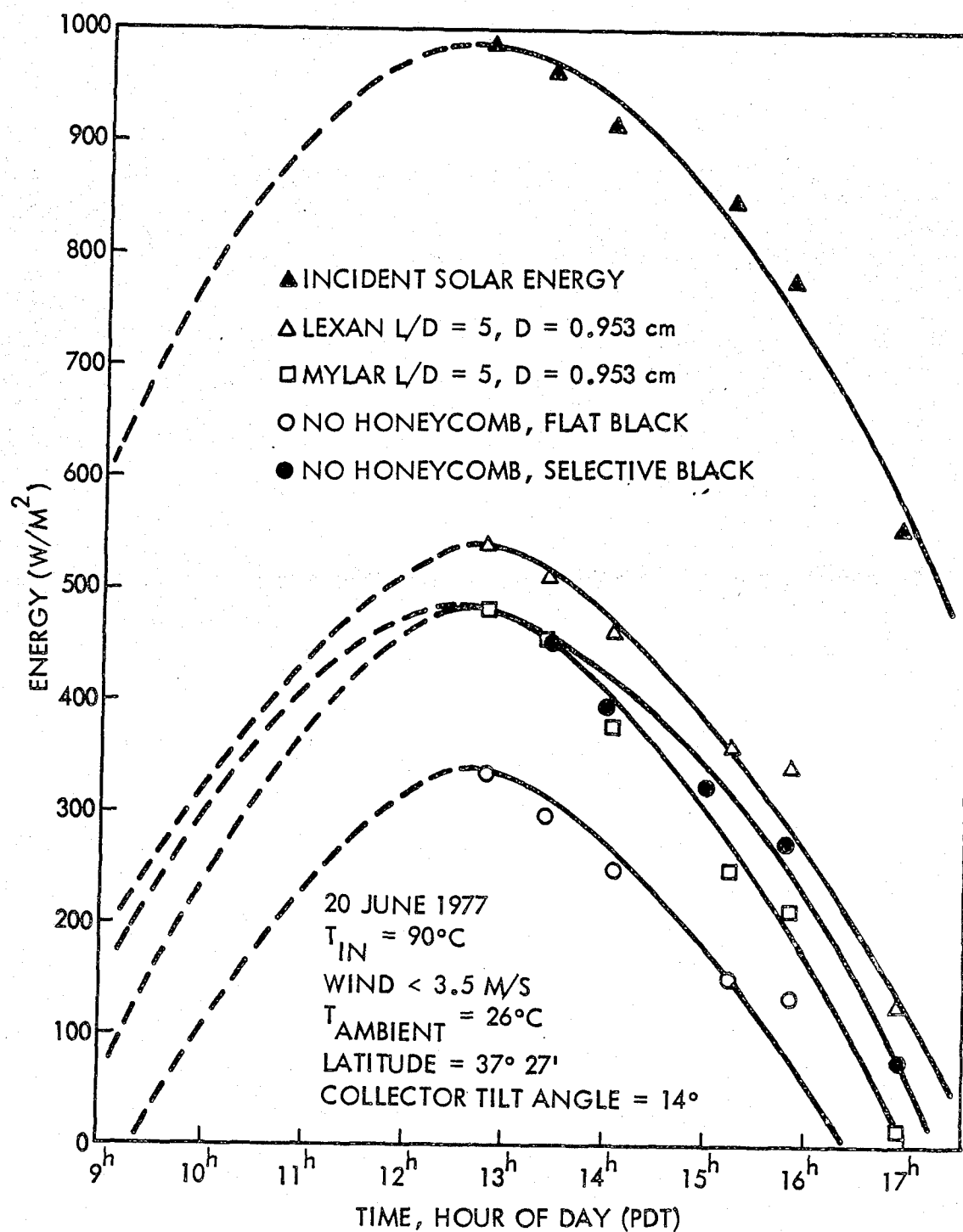


Fig. 3-20 Comparison of Diurnal Performance Between Glass Covered Flat Black Honeycomb Collector, and a Selective Black, No Honeycomb Collector

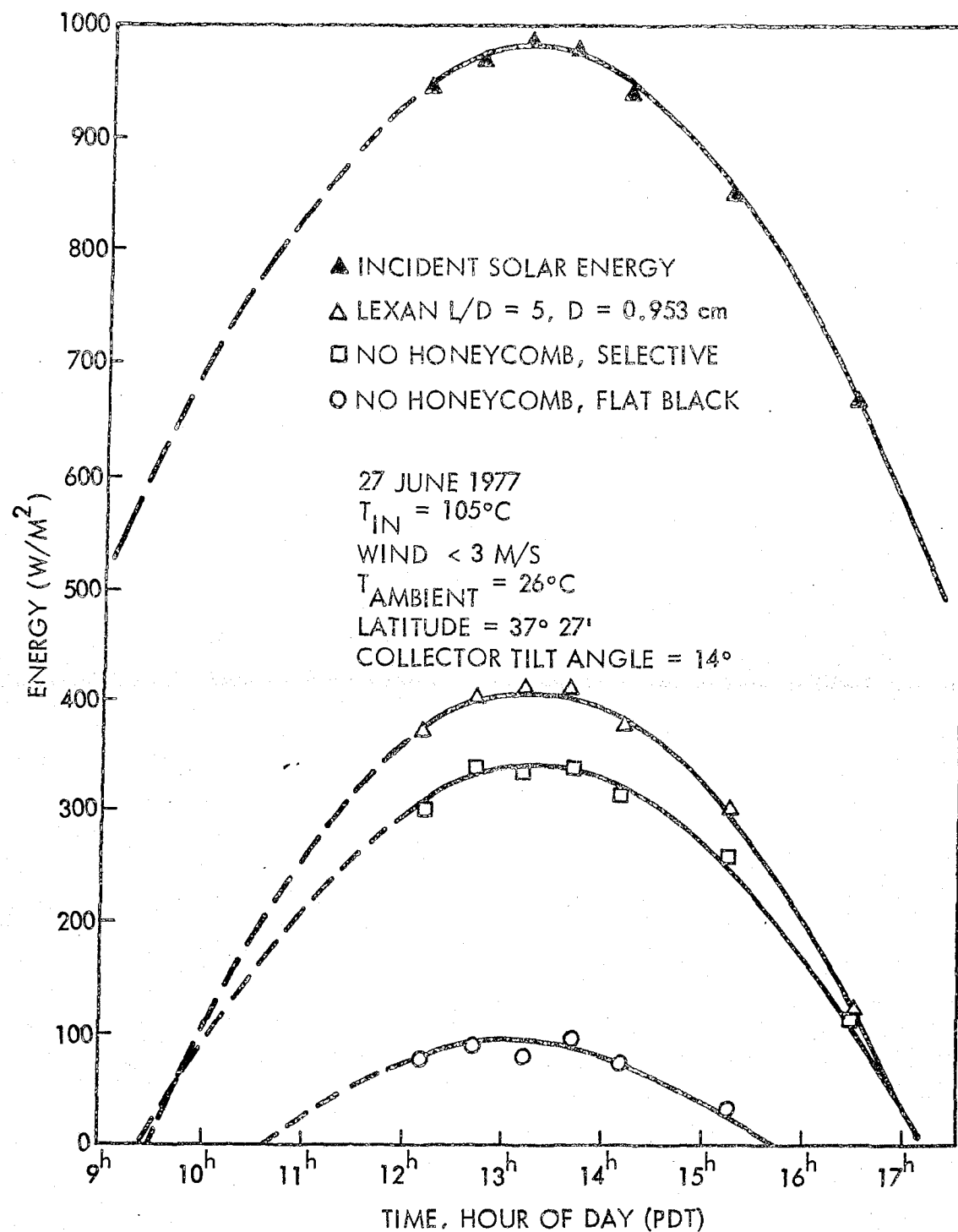


Fig. 3-21 Comparison of Diurnal Performance Between a Flat Black Hexcel Lexan Honeycomb Collector, and Selective Black No Honeycomb Collector

Figure 3-22 shows the comparison between the measured efficiencies and those predicted by the SOLAR computer program (Ref. 3). In all instances the predicted efficiency is higher than the measured value. The reasons for this discrepancy are not fully understood at this time, although two contributing effects are thought to be the presence of temperature gradients in the collector leading to erroneous results and possible inaccuracies in the present theory dealing with plastic honeycomb.

3.4 TRANSPARENT PLASTIC COVERS

Depending upon their end use, solar collector systems use one or two covers in an effort to increase their efficiency by reducing the heat losses. For heating in cold climates, hot water heating, and for air conditioning applications, nonhoneycomb collectors are used with either a selective black absorber with one or two covers or a flat black absorber with two covers. The cover materials used are either glass or plastic with the former preferred for high-temperature collectors since it is opaque in the longer wavelength region and hence improves the efficiency by reducing re-irradiation of the energy to the sky. The plastics, on the other hand, are much cheaper and afford a weight saving and therefore offer an attractive alternative when used in conjunction with a honeycomb system.

3.4.1 The Effect of Cover Material on Collector Performance

The three cover materials evaluated in this program were glass, Tedlar, and FEP Teflon. The glass chosen for evaluation was a high-transmission, low-iron content, tempered ASG Sunadex glass, 0.475 cm (3/16 in.) thick, while the Tedlar, a duPont product, was 0.0102 in. (4 mil) thick and the duPont FEP Teflon 0.00265 cm (1 mil) thick. The pertinent optical properties of the three materials are given in Table 3-1, from which it can be seen that although the FEP Teflon has the highest solar transmission, it also has the highest transmission at the longer wavelength, thereby allowing energy to be radiated directly to the sky when used in conjunction with a flat black absorber. Although both the glass and the Tedlar exhibit the same solar transmission

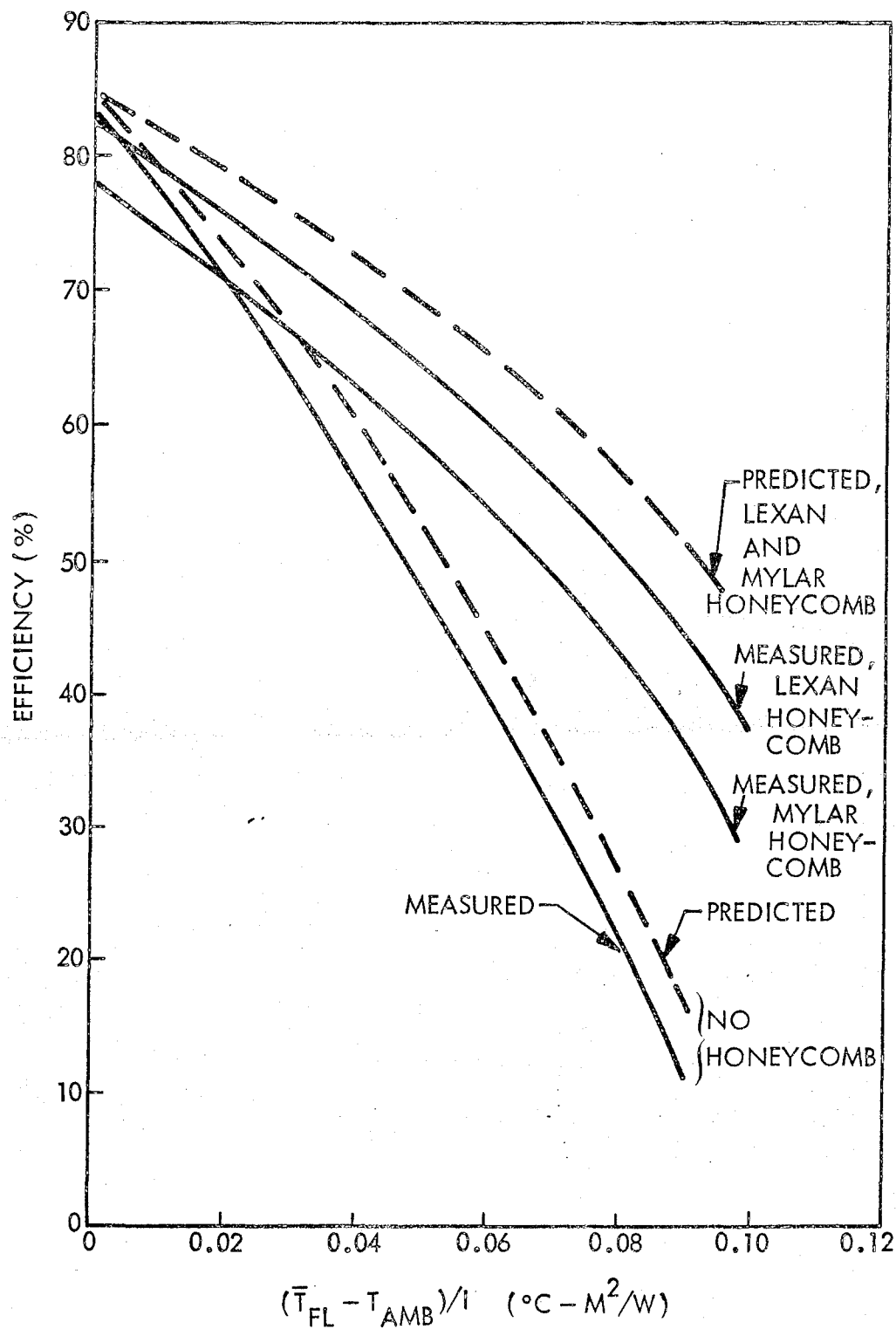


Fig. 3-22 Comparison of Predicted to Measured Performance

Table 3-1
RADIATION PROPERTIES OF THREE COVER MATERIALS

Item	ASG Glass	FEP Teflon	Tedlar
<u>Thickness</u>			
mm	4.76	0.0254	0.102
in.	0.1875	0.001	0.004
<u>Solar Spectrum</u>			
Transmittance	0.91	0.95	0.90
Reflectance	0.08	0.04	0.08
Absorptance	0.01	0.01	0.02
<u>Long Wavelength Spectrum</u>			
Transmittance	0.00	0.58	0.33
Reflectance	0.15	0.07	0.08
Absorptance	0.85	0.35	0.59

characteristics, the glass is much more efficient at the longer wavelengths where it is essentially opaque and therefore does not radiate directly to the sky. Based upon these characteristics, it is apparent that a flat black collector would be more efficient at the low temperatures with a FEP Teflon cover since heat losses are low; at high-temperature operation, on the other hand, the glass-covered system becomes more efficient since the heat losses, which are important, are reduced by the absorptance of the glass.

The addition of a honeycomb to any one of these systems enhances its performance. However, the improvement in performance at high temperatures with the Teflon or Tedlar system will be greater than that experienced by the glass-covered system since one of the major drawbacks of the plastic cover, the large radiation heat loss directly from the absorber plate to the sky, is markedly decreased. At the low temperatures, the FEP Teflon/honeycomb system is expected to outperform the glass/honeycomb collector.

In this test series, the Lockheed-designed collectors were used and the testing performed in accordance with NBS procedures (Ref. 8). Three separate series were run in which two identical flat black absorber collectors were used, one with honeycomb and the other without honeycomb. The honeycomb used in all these tests was a Hexcel Lexan honeycomb with an aspect ratio (L/D) of 5.

Figure 3-23 illustrates the difference in instantaneous efficiencies for the three systems tested. As expected, the Teflon-covered system with no honeycomb is the most efficient at the low temperatures, while the glass-covered system is the most efficient at the high temperatures. With Lexan honeycomb, the Teflon-covered collector is the most efficient collector over the entire temperature range; the difference once again is greatest at low temperatures. The Tedlar and glass-covered collector performance were the same, indicating that the honeycomb equalized the heat losses for the two designs. Also, using honeycomb with the plastic-covered collectors gives a performance 40 percent greater than a nonhoneycomb collector at the high temperatures ($\Delta T/I \geq 0.08^\circ\text{C} - \text{M}^2/\text{W}$).

The diurnal performances with Teflon, Tedlar, and glass covers are shown in Figs. 3-24, 3-25, and 3-9, respectively, for an inlet fluid temperature near 90°C . The tests were performed on different days with slightly different weather conditions and tilt angles; however, the honeycomb and nonhoneycomb results are comparable. The diurnal performances are summarized in Table 3-2. The primary observation concerning the diurnal performance is that no major differences exist between the diurnal and instantaneous results; i.e., no changes occur with incident angle.

3.5 THERMAL PROTECTION STUDIES

Previous studies have demonstrated improved efficiencies due to the use of honeycombs fabricated from low-temperature plastics such as Lexan and Mylar. However, these low-temperature plastics suffer from the problem that if the fluid passing through the collector is stopped for some reason (e.g., pump failure), the absorber plate in the

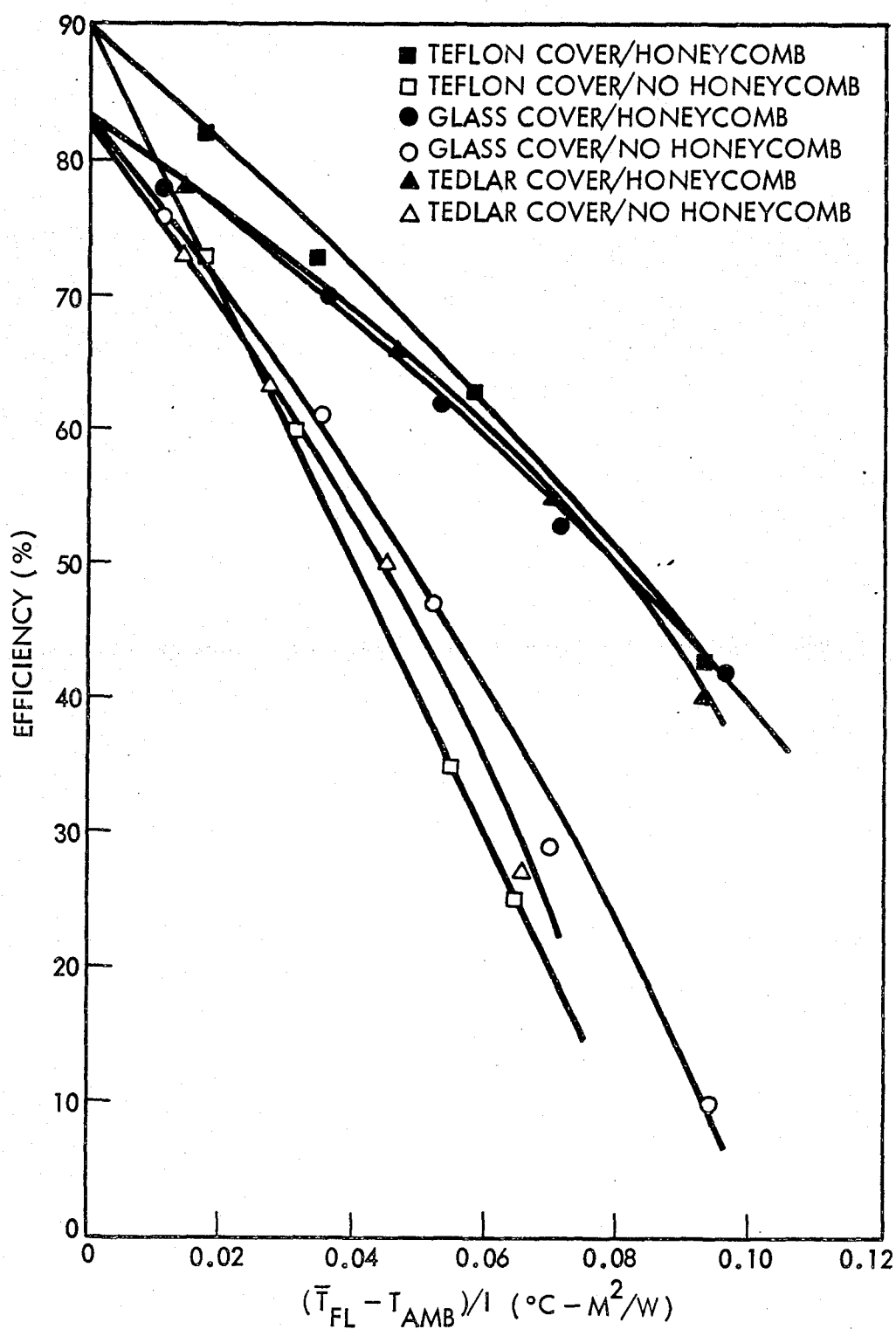


Fig. 3-23 Effect of Hexcel Lexan Honeycomb on the Performance of a Flat Black Collector With Glass, Tedlar, and Teflon Covers

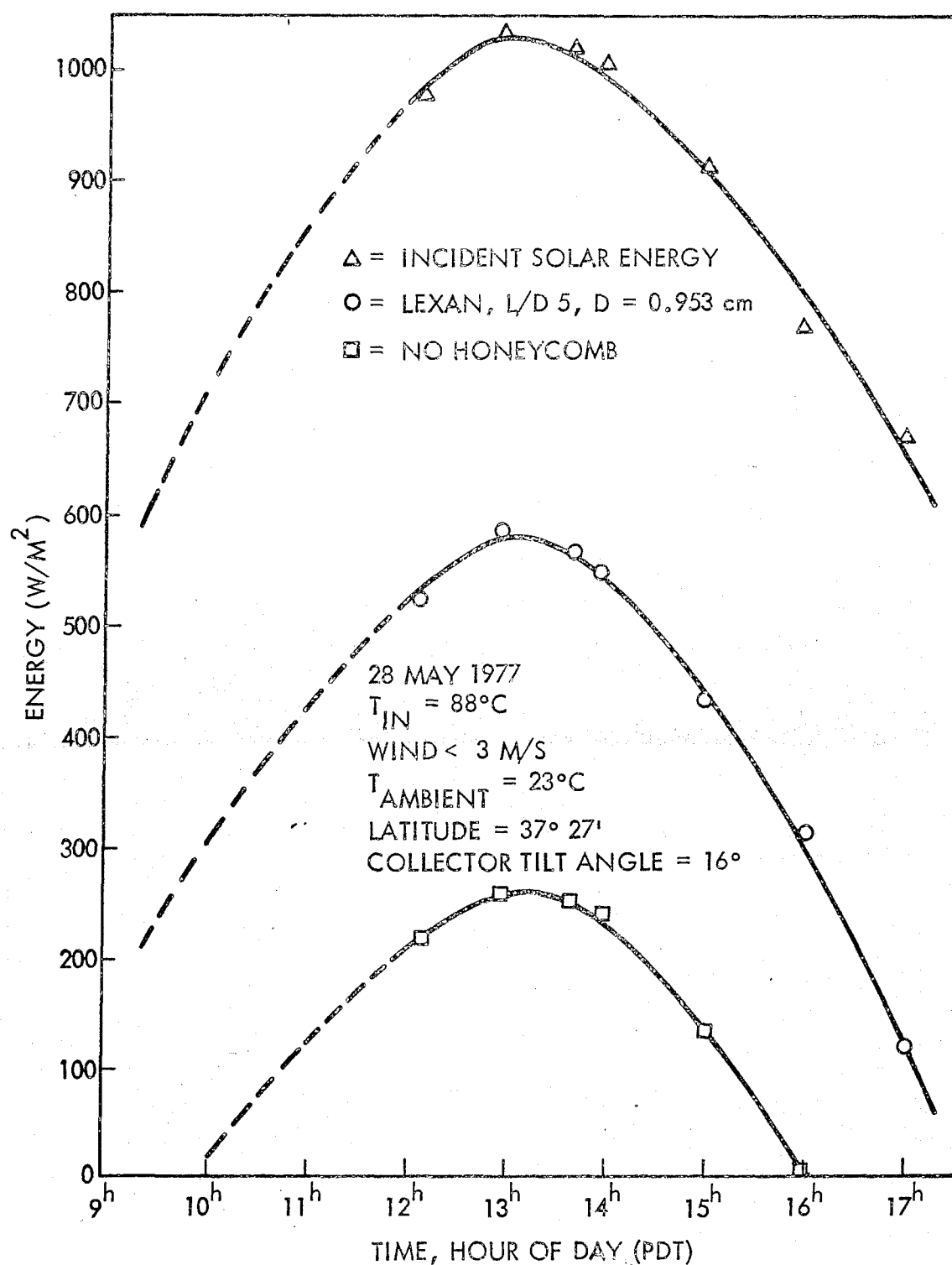


Fig. 3-24 Diurnal Performance of a Teflon Covered Collector With Flat Black Absorber Plate With and Without Hexcel Lexan Honeycomb

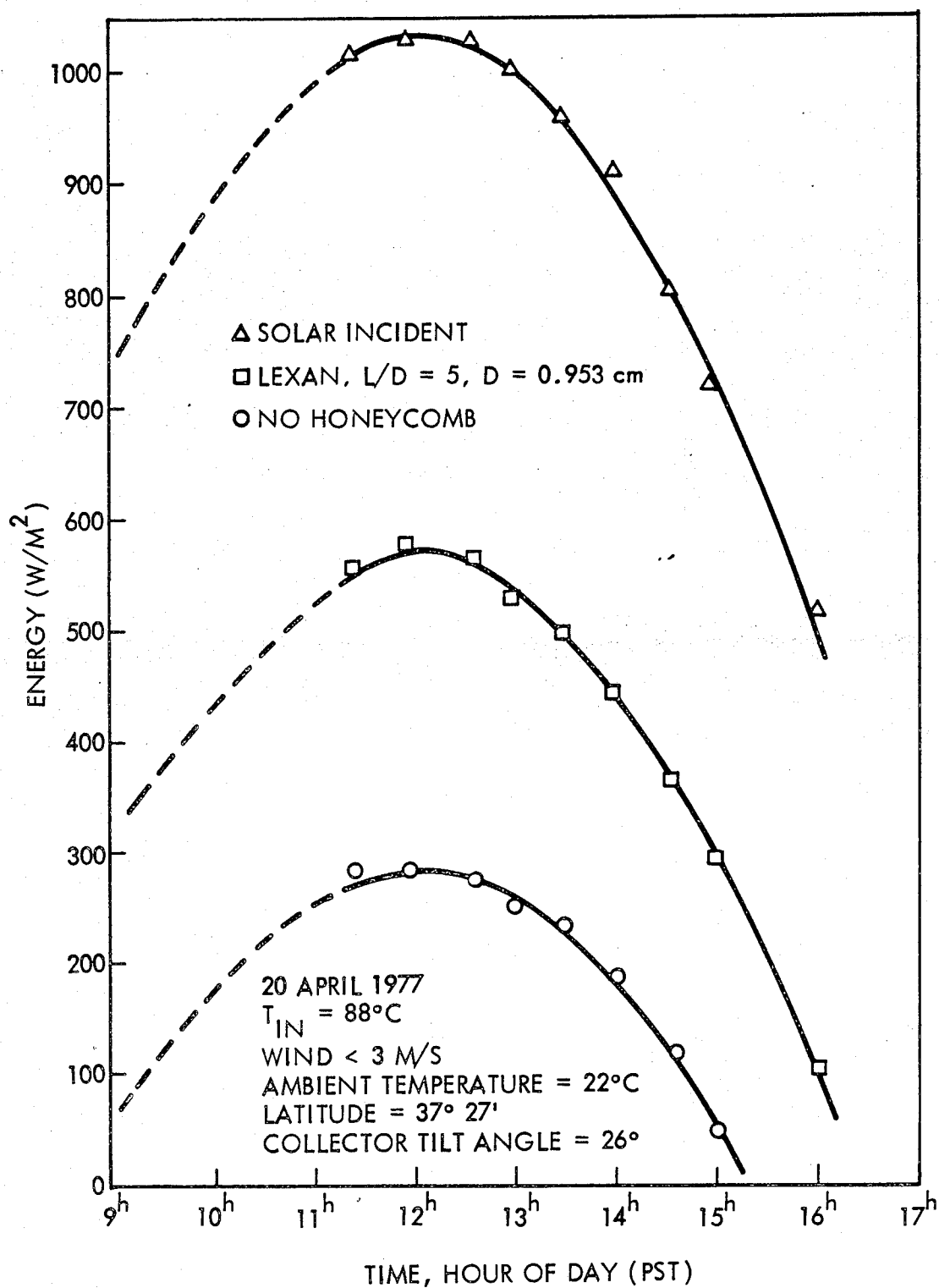


Fig. 3-25 Diurnal Performance of Tedlar Covered Flat Black Collector With and Without Hexcel Lexan Honeycomb

Table 3-2
DIURNAL PERFORMANCE FOR COLLECTORS WITH VARIOUS COVERS

Inlet Temperature of 90°C
Hexcel Lexan Honeycomb, L/D = 5

Item	Useful Energy Collected (W-hr/m ²)	Diurnal Efficiency
<u>Teflon Cover</u>		
No Honeycomb	1005	0.13
Honeycomb	3290	0.42
<u>Tedlar Cover</u>		
No Honeycomb	1200	0.16
Honeycomb	3230	0.43
<u>Glass Cover</u>		
No Honeycomb	1430	0.18
Honeycomb	3210	0.41

collector reaches such a high equilibrium temperature that the honeycomb adjacent to the absorber plate may fail thermally. For example, it may change its shape or become opaque. Such failures depend on the honeycomb material and the collector absorber coating. (Under normal conditions, the plate is cooled by the fluid so that its temperature is below the acceptable operating temperature.) The purpose of this part of the contract is to study ways to prevent damage to the honeycomb.

3.5.1 Thermal Protection Techniques

One possible solution is to use free convection to provide the necessary cooling. Ordinarily, free convection in a honeycomb is suppressed by the honeycomb. However, this suppression is effective only up to a particular temperature difference (corresponding to the critical Rayleigh number); when the temperature is exceeded, free

convection currents set in with a consequent heat loss. If the honeycomb were designed in such a way that the free convection set in just above the design plate temperature, the free convection currents would cool the plate once the plate exceeded the critical temperature. The resultant equilibrium temperature would therefore be much lower than if the free convection were suppressed right up to the equilibrium temperature. It may even be less than the degradation point of the plastic.

To test this hypothesis, the computer program SOLAR was used to simulate the collector and calculate the equilibrium temperature. (Obviously, a reliable equation for the post-stability free convection heat transfer was required. Until recently, such an equation was not available for an inclined honeycomb but the recent equation of Hollands et al., Ref. 1, is now incorporated into SOLAR.) A set of "worst-case" ambient conditions was chosen for the simulation since the honeycomb collector must be able to withstand the most severe climatic conditions without deterioration. The conditions chosen were:

Incident Solar Energy	=	985 W/m^2 (313 Btu/hr-ft ²)
Sun Angle	=	0 deg
Ambient Temperature	=	38°C (100°F)
Wind Velocity	=	0
Collector Tilt	=	45 deg

The collector was assumed to have a glass cover, an absorber plate with solar absorptance of 0.95, and a backside conductance of $0.68 \text{ W/m}^2 \text{ K}$. The solar transmittance of the honeycomb was assumed to be 100 percent, which most honeycombs approach at near normal incidence.

The depth of the honeycomb, L , was fixed at 5.08 cm (2 in.). For absorber plate operating temperature of 93°C (200°F), free convective currents are just suppressed at this condition if L/D is made equal to 4.

Table 3-3 gives the results for both selective surface and black-painted absorber plates and for various aspect ratios. The maximum continuous service temperature for Mylar

is about 135°C (275°F), and for Lexan about 150°C (300°F). Thus, neither honeycomb material could withstand prolonged exposure under any of the conditions shown in Table 3-3. Consequently, natural free convective cooling was found to be unsatisfactory for low-temperature plastics. The chief reason for the higher-than-expected calculated equilibrium temperatures was that the density and expansion coefficient of the air both decrease with increasing average air temperature. Accordingly, the potential for free convection (i.e., the Rayleigh number) increases very slowly as the temperature difference increases. The increase is much slower than if the air properties remain constant.

Table 3-3
PREDICTED EQUILIBRIUM TEMPERATURE
OF PLASTIC HONEYCOMBS

L/D	Black-Painted Absorber Plate	Selective Surface Absorber Plate $\epsilon = 0.15$
3	176°C (350°F)	229°C (445°F)
4	188°C (370°F)	257°C (495°F)
10	216°C (420°F)	265°C (510°F)

The maximum continuous service temperature for FEP Teflon is about 210°C (410°F). Teflon should, therefore, survive no-flow exposure with a black-painted collector plate, but some difficulties could be encountered with a selective surface absorber plate.

Other methods of thermal protection were also considered, including gravity-fed reservoirs and thermal syphoning, but both of these techniques had several drawbacks because of increased component complexity and hence increased system cost. The method which offered the most promising chance of success was based upon techniques for thermally isolating the honeycomb from the absorber surface either by low-conductivity spacers or by bonding the honeycomb to the underside of the collector cover.

To evaluate this method of isolation, two wooden stagnation boxes were designed and built and consisted of an absorber plate, 0.0929 m^2 (1 ft^2), 10.2-cm (4-in.) bottom rigid urethane foam and 7.62-cm (3-in.) side foam. The spacing between the cover and the honeycomb and the honeycomb and the absorber plate could be varied. Two types of absorber plates were used, a selective black-coated copper plate ($\alpha_s/\epsilon = 0.97/0.92$). Figure 3-26 shows the stagnation boxes mounted on the test rack with an FEP Teflon cover with and without reinforcing.

To eliminate the effect of weather variables, the two identical stagnation boxes were used, one with honeycomb and the other without honeycomb in all the tests performed. Temperature measurements were made at the center of the cover and at four locations on the absorber plate. In some of the tests, the temperature of the honeycomb close to the absorber plate was measured. When mounted on the rack, the boxes were tilted so as to be normal to the sun at solar noon. Testing was only carried out on clear sunny days.

Mylar Honeycombs/Flat-Black Absorber. A sample of Hexcel Mylar honeycomb ($L/D = 5$) was tested with the flat-black absorber plate. With the honeycomb resting on the absorber plate, an equilibrium temperature of 155°C was reached after 2 hr; in the no-honeycomb box, the equilibrium temperature attained was 120°C . The test was repeated with the Mylar honeycomb raised 0.31 cm ($1/8$ in.) above the absorber plate by means of glass rod spacers; again, the equilibrium temperature reached was 155°C . A similar test was performed at the Hexcel Corporation Test Laboratory in which the Mylar honeycomb ($L/D = 5$) was resting on the absorber plate. In this case, the Mylar degraded along the glue lines after a period of time.

Lexan Honeycomb/Flat-Black Absorber. Both the Hexcel and Norfield Lexan were evaluated in this test series. In tests with the Norfield Lexan honeycomb ($L/D = 3.7$), the absorber plate equilibrium temperature was 144°C after 3 hr, for both the honeycomb in contact with the absorber plate, and with the honeycomb raised 0.31 cm ($1/8$ in.) by means of the glass rod spacers. With the Hexcel Lexan honeycomb ($L/D = 5$) in contact with the absorber plate, the plate quickly reached 166°C , which

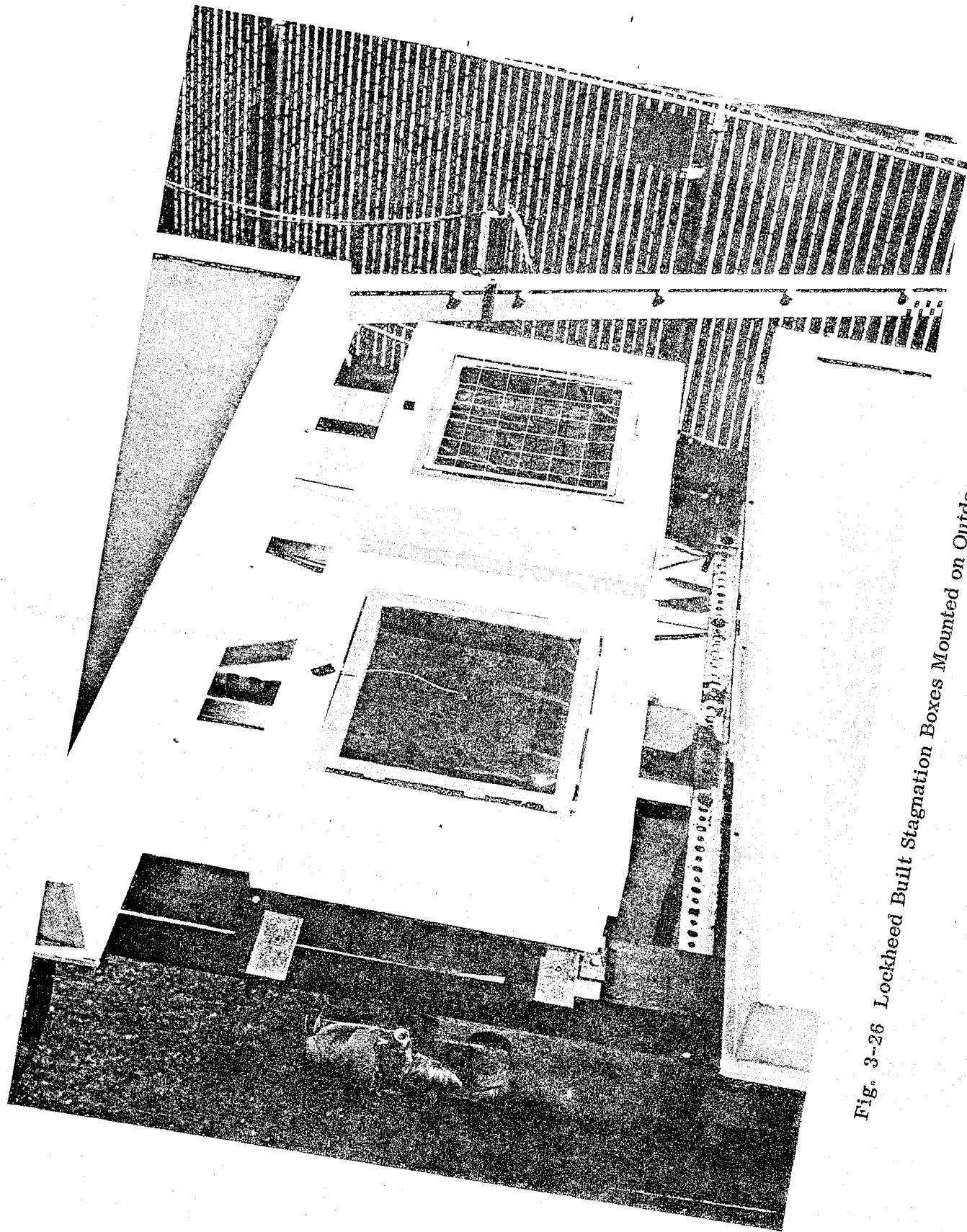


Fig. 3-26 Lockheed Built Stagnation Boxes Mounted on Outdoor Test Rack

was very close to the maximum operating temperature of the Lexan, so that the test was terminated to prevent honeycomb failure. Inspection of the honeycomb indicated that the Lexan had started to curl at the cell ends in contact with the absorber plate because of material softening. The test was repeated with the honeycomb raised 0.31 cm (1/8 in.) above the absorber plate by attaching it to the glass cover. Table 3-4 gives the results obtained for two spacing values from which it can be seen that the stagnation temperature can be lowered and thereby safeguard the honeycomb and over-all collector safely.

Table 3-4
EFFECT OF SPACING ON HONEYCOMB EQUILIBRIUM TEMPERATURES

Honeycomb Spacing (cm)	No Honeycomb	With Honeycomb	
	Absorber Plate Temperature (°C)	Absorber Plate Temperature (°C)	Honeycomb Temperature (°C)
0	125	166	166
0.31 - 0.63	125	144	132
1.27	123	127	107

Further testing is still required to be done in order to complete the correlation between the spacing and equilibrium temperature for the various plastic honeycombs using different spacing techniques, but indications are that the technique offers a possible solution to the problem of stagnation.

Stagnation tests have been performed by Hexcel Corporation on Lexan honeycomb (Ref. 12), $L/D = 5$, in which the Lexan was allowed to rest on the absorber plate. The temperature of the plate exceeded 160°C for 4 hr each day with a maximum of 177°C being attained on one occasion. After two weeks, the honeycomb showed no change in physical appearance, but on further testing the cell ends in contact with the absorber plate began to curl because of material softening as witnessed in the Lockheed tests. No adhesive degradation was observed.

Section 4

CONCLUSIONS AND RECOMMENDATIONS

The objective of the program, to develop an optimized transparent plastic honeycomb-covered solar collector, was achieved. Cost studies, fabrication techniques, various cellular structure configurations, and high-temperature stability tests were performed. A high-temperature plastic, FEP Teflon, and two low-temperature plastics, Mylar and Lexan, were analyzed and tested. Tests and analyses using plastic covers were performed. The major conclusions from the program are as follows:

- For a conventional single-glazed solar collector with a flat-black absorber, incorporation of Lexan honeycomb provides a substantial performance improvement, with concomitant reduction of initial system costs.
- Based on performance, cost, and producibility criteria, the optimum low-temperature plastic honeycomb utilizes Lexan core with a length of 4.76 cm (1-7/8 in.) and cell diameter of 0.95 cm (3/8 in.).
- FEP Teflon honeycomb is currently not economically feasible.
- Teflon covers in conjunction with honeycomb provide marginally better performance than glass or Tedlar.
- No appreciable increase in collector performance is achieved by the use of honeycombs with selective black absorbers.
- Maintenance of a gap between the honeycomb and absorber plate shows promise of providing passive thermal protection of plastic honeycomb during collector stagnation conditions.

To fully qualify the honeycomb concept as an integral component of low-cost, high-efficiency solar collector systems with respect to general acceptance within the solar collector manufacturing industry, the following efforts are recommended for additional study:

- Continue to update the honeycomb analytical model, the "SOLAR" computer program.

- Further develop, refine, and test practical honeycomb thermal protection techniques.
- Select commercially available flat-black absorber collectors for long-term testing of Lexan honeycomb system:
 - (1) Lexan Honeycomb, Glass Cover, Chamberlain Collector
 - (2) Lexan Honeycomb, Plastic Cover, Chamberlain Collector
- Work closely with Hexcel Corporation to optimize the Lexan honeycomb system at low cost.

Section 5
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A.1 EXPERIMENTAL PERFORMANCE OF PLASTIC HONEYCOMB
IN FLAT-PLATE SOLAR COLLECTORS

by

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A.1 EXPERIMENTAL PERFORMANCE OF PLASTIC HONEYCOMB IN FLAT-PLATE SOLAR COLLECTORS

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ABSTRACT

A test program was carried out to evaluate the performance of solar collectors containing hexagonal shaped honeycomb made from thin-film plastics of Lexan*, Mylar**, Tedlar**, and Kapton**. Testing was conducted simultaneously on both honeycomb and non-honeycomb collectors to obtain a direct comparison of performance. Both flat black and selective black collectors were evaluated over the temperature range of 313°K (104°F) to 395°K (250°F). Results confirmed that properly designed plastic honeycomb collectors provide a significant improvement in performance over that of nonhoneycomb collectors. Instantaneous efficiencies above 50 percent (50%) were obtained for operating temperatures up to 383°K (230°F). Comparison of diurnal operation between honeycomb and nonhoneycomb collectors shows even larger increases in performance by the honeycomb collectors for those plastics which are highly transparent to solar energy.

INTRODUCTION

The need for development of high efficiency, cost effective solar collectors for high temperature applications involving solar driven air conditioners and for heating of buildings in cold northerly climates led researchers to consider the use of transparent honeycomb to improve collector efficiency. Previous work by various investigators indicated that collector efficiency could be significantly increased by placing transparent honeycomb of proper design between the absorber plate and transparent glazing as shown in Fig. 1. The honeycomb is instrumental in reducing collector convective and radiative heat losses. Initial experimental studies at Lockheed in 1973 on Mylar honeycomb (1) indicated the potential of thin-film plastics for this application. Subsequently, a comprehensive analytical and experimental program was undertaken to confirm these results and to develop a plastic honeycomb system that was optimum in terms of performance and cost. This paper presents results from the first phase of that effort. Economical considerations in designing with plastic honeycombs are presented in Reference 2.

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HONEYCOMB MATERIALS AND CONFIGURATIONS

Various honeycomb sections were fabricated using Lexan (polycarbonate) Type 8073-112, Mylar (polyester) Type S, Tedlar (polyvinyl fluoride) Type BG20TR, and Kapton (polyimide).

The configurations tested are shown in Table I. A standard hexagonal cell configuration produced by Hexcel, Dublin, California, was used in construction of the honeycomb as shown in Fig. 2.

Lexan honeycomb was found to be the easiest to fabricate; therefore, honeycomb specimens of this material were constructed in two different cell diameters (i.e., 0.476 and 0.953 cm, as shown in Table I). It was thus possible to compare the performance between two different cell diameters for the same material and equivalent L/D ratios. The range of aspect ratios from one to ten for the Lexan honeycomb provided a sufficiently wide range to study for collector applications. Although the cell diameters used for the study were chosen on the basis of ease of fabrication and the availability of existing tooling, they represent sizes typical for collector applications.

Selection of the above materials for honeycomb evaluation was made after screening a number of candidates. The selection was made based on considerations of optical properties, environmental stability, honeycomb fabrication, and product cost. These materials provided a range of variation in properties and cost from which a reasonable comparison could be made. As the test program progressed, the best performing materials were selected for more thorough study and the poorer performances were eliminated as candidates.

The single film optical properties of each plastic are given in Table II. The solar transmission (τ_s) of each plastic is high (86-91%) except for Kapton which was measured to be 69%. For the film thicknesses shown all the materials are somewhat transparent to infrared radiant energy. The solar and infrared properties of the thin films are directly correlative with the resultant performance of the honeycomb collectors as discussed in Ref. 3.

TEST PROGRAM

Full scale honeycomb collectors containing the four plastic honeycombs were constructed and tested under ambient weather conditions at the Lockheed solar collector test facility in Palo Alto, California (37° 27' North Latitude). Testing was conducted in accordance with procedures recommended by NBSIR 74-635 (4). During the multi-faceted test program, testing was conducted simultaneously on both honeycomb and nonhoneycomb collectors to obtain a direct comparison of performance. Both flat black and selective black collectors were evaluated. Collector performance

was determined over the temperature range of 313°K (104°F) to 395°K (250°F).

Tests were simultaneously conducted on up to four collectors to provide a direct comparison of performance. The parameters controlled during the tests included fluid inlet temperature, flow rate, and collector orientation with respect to the solar vector. Measurements were made of inlet and outlet fluid temperatures, ambient air temperature, wind velocity and direction, relative humidity, and both total and diffuse solar irradiation using pyranometers located in the plane of the collectors. The flow rate of the heat transfer fluid was maintained constant during all tests, with the flow rate for the four collectors being 30.36, 31.86, 33.31, and 33.59 kg/hr, respectively. A majority of the tests were performed with the tilt angle of the test rack adjusted so that each collector surface was normal to the solar vector at solar noon.

The absorber panels for the four test collectors were 43 x 127 cm (17 x 50 in.) in size. These panels were 0.16 cm (1/16 in.) thick, parallel flow, aluminum "roll-Bond" procured as off-the-shelf items from Olin Brass Company, East Alton, Illinois. Each panel was precoated with a flat black paint or selective coating and assembled into the collector test units such that the spacing between the absorber and cover glass was approximately equal to the "L" dimension of the plastic honeycomb. The honeycomb sections were assembled in each collector so that they were in contact with the absorber plate and not more than 0.813 mm (1/32 in.) from the cover glass.

The flat black absorber coating consists of Chemglaze Z306 polyurethane black which had an α_s of 0.95 and an ϵ of 0.92. The selective coating was a vacuum deposited multilayer coating with an $\alpha_s = 0.95$ and $\epsilon = 0.18$.

RESULTS AND DISCUSSION

Test results are presented for the honeycomb and nonhoneycomb collectors in terms of both instantaneous efficiency and diurnal performance. Instantaneous efficiency is given as a function of $(T_{\text{FL}} - T_{\text{AMB}})/I$, i.e., $\Delta T/I$. Diurnal performance is presented in terms of energy per unit area collected over several hours of operation for a given day.

Results of instantaneous efficiency as a function of $\Delta T/I$ for Lexan, Mylar, and Kapton honeycomb in collectors with flat black absorber coatings are given in Fig. 3. The results presented in this and the other figures contained herein are from experimental data. The data points have been deleted for clarity. Each honeycomb collector had only one glazing, and the glazing for all collectors were of the same type of glass with essentially identical transmission. All collectors had equivalent amounts

of insulation to give an equivalent conduction heat loss.

The results presented in Fig. 3 show Lexan to be the best performer of the honeycomb materials. Both Mylar and Kapton have lower solar transmittances than Lexan with Kapton being much lower than Mylar. This is the primary reason for the poorer performances of Mylar and Kapton honeycombs. In this regard, Mylar should give higher efficiencies than Kapton. The similar performances of the Mylar and Kapton honeycomb collectors shown here may have been caused by the uniqueness of this particular Mylar honeycomb specimen which had to be made from two different sections, i.e. an $L/D = 3$ and an $L/D = 2$ to be equivalent to $L/D = 5$. Since stacking of the two sections did not provide straight through honeycomb cells, the transmission of this particular Mylar honeycomb may have been lower than for a homogenous system.

All honeycomb collectors showed better efficiency than the non-honeycomb collectors at values of $\Delta T/I > 0.02$.

Tedlar honeycomb failed mechanically during the initial series of tests thus no data is available for this material. It was found that Type BG20TR Tedlar in honeycomb form had a tendency to shrink as collector temperatures were increased above ambient temperatures. For this reason, Tedlar was eliminated from further testing and is not considered to be a good material for honeycomb applications.

The diurnal performances of flat black painted collectors containing Lexan, Mylar, and Kapton honeycombs are shown in Fig. 4. These results are for the collectors operating at an inlet temperature of 106°C . The higher solar transmission of the Lexan honeycomb and its influence on all day performance is evident from these curves. The difference in performance between the different materials at solar noon is due primarily to the higher absorption of the diffuse component of solar energy by the Kapton and Mylar.

To evaluate the effect of honeycomb L/D ratio and cell diameter on collector performance, various configurations of Lexan honeycomb were tested. Results of this evaluation are shown in Fig. 5 where instantaneous efficiency is plotted as a function of $\Delta T/I$. The resultant effects of different honeycomb aspect ratios on collector efficiency are vividly displayed by the data. Collector efficiency increases as the honeycomb L/D ratio increases, with the nonhoneycomb collector exhibiting the poorest performance. This set of curves is also typical for the Mylar and Kapton honeycombs, except that these materials had correspondingly lower performances because of their lower solar transmittances.

The increase in honeycomb collector efficiency shown in Fig. 5 is due to a reduction in convection and radiation heat losses as the L/D ratio increases. The reduction in radiation losses can be related to the effective emittance of the honeycomb/absorber system which decreases as the honeycomb L/D ratio increases, as presented in detail in Ref. 3. For the test conditions and honeycomb aspect ratios greater than 2 as reported herein, convection suppression, as defined by Hollands, et. al. (5) has occurred. For such cases, the heat transfer through the air is by conduction, and as such, is linearly dependent on honeycomb cell length (L).

Figure 5 shows the increasing influence on efficiency by the honeycomb aspect ratio as the $\Delta T/I$ term increases. As collector temperatures rise, the reradiation term becomes more significant. Therefore, the reduced effective emittance of the larger L/D honeycombs becomes an important factor in reducing collector heat losses.

When the two best performing Lexan honeycomb collectors are compared, it is seen that the collector with $L/D = 10$ and $D = 0.476$ cm has higher efficiency than the one with $L/D = 5$ and $D = 0.953$ cm. Since convection is suppressed and the cell lengths are equal, the difference in efficiency is attributed to the difference in radiation heat loss due to change in effective emittances as a function of the L/D ratio. A more thorough discussion of the effects of the L/D ratio on radiation and convection heat losses can be found in Refs. 3 and 6.

Figure 6 shows the diurnal performance of a Lexan honeycomb collector compared to double and single glazed nonhoneycomb collectors, all containing a flat black absorber coating. The data is for a collector inlet temperature of 104°C and ambient temperature of 22°C . It is significant to note the continued higher performance of the Lexan honeycomb collector at high solar incident angles. This illustrates that a properly designed honeycomb collector will collect more energy over a daily period than comparable nonhoneycomb collectors.

The instantaneous efficiencies of various selective coated collectors containing Lexan honeycomb are presented in Fig. 7, and a comparison is made with a similar nonhoneycomb collector. For all cases shown, the honeycomb improves the efficiency over that of the nonhoneycomb collectors. With a selective coating the emittance is low both with and without honeycomb so the difference in performance is due to changes in convection heat loss. Even the $L/D = 2$ provides increased performance over the nonhoneycomb collector because of the convection heat loss suppression. The Lexan honeycomb collector with $L/D = 5$, $D = 0.953$ cm had essentially the same performance as the $L/D = 10$, $D = 0.476$ cm honeycomb since the convection suppression is the same in both cases and the emittance is low giving equal radiation losses.

The diurnal performance of a Lexan honeycomb collector is compared to that of a single-glazed nonhoneycomb collector in Fig. 8, both equipped with identical selective coatings. Again, the honeycomb collector outperformed the nonhoneycomb collector in the daily collection of energy. The performance of a single-glazed flat black nonhoneycomb collector is shown in Fig. 8 for comparison.

CONCLUSIONS

From the results obtained during this test program, it is concluded that properly designed honeycomb will provide substantial improvements in efficiency over that of comparable nonhoneycomb collectors over the operational temperature range of 70 to 120°C. This was found to be true for both flat black and selective coated systems. Both the instantaneous efficiency and diurnal performance was better for properly designed honeycomb collectors. The honeycomb achieves the improved performance by reducing the convection and radiation heat losses for the flat black coated collectors and through reduction of convection heat losses for the selective coated collectors.

A flat black collector with honeycomb has approximately the same instantaneous efficiency as a selective coated nonhoneycomb collector. Thus, in some cases a trade off in cost can be made between the honeycomb and selective coating.

The amount of convection and/or radiation heat loss suppression is dependent on the honeycomb L/D ratio and on the cell length (L) and diameter (D).

Of the four plastic honeycomb materials evaluated, Lexan was the best performer followed by Mylar which has poorer performance because of increased solar absorptions and light scattering properties. Kapton was found to be unacceptable because of poor diurnal performance due to its high solar absorbing properties and due to the extremely high cost of the material. Tedlar (Type BG20TR) was found unacceptable as a honeycomb material because of its tendency to shrink and change shape at only moderately high temperatures.

Lexan honeycomb showed excellent performance at operating temperatures up to 400°K (260°F). This material has been shown to be cost effective (2), and can be manufactured using existing fabrication methods with minor alterations. There is some question, however, regarding the long term durability and stability of Lexan honeycomb, and further work is required to evaluate this for collector applications.

Maximum efficiency for honeycomb collectors is achieved using only one transparent cover glass. Therefore, a cost tradeoff can be made between the cost of the honeycomb and the cost of the second glass cover typically used on conventional high

performance flat plate collectors. This cost tradeoff combined with the improved performance of a honeycomb collector can result in a potential cost reduction for the overall solar collector system.

In summary, properly designed plastic honeycombs provide significant improvements in solar collector performance. Plastics such as Lexan (polycarbonate) are presently usable for honeycombs. However, further development is required to optimize honeycomb geometry and improve manufacturing techniques leading to more efficient use of materials and additional reduction in costs. In addition, the long term reliability and durability of the materials must be evaluated before full implementation of plastic honeycombs can be a reality.

ACKNOWLEDGEMENTS

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Paper: Experimental Performance of Plastic Honeycomb in Flat-Plate Solar Collectors

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- II. Single Film Optical Properties

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- Figure 2. Honeycomb Hexagonal Cell Configuration
- Figure 3. Efficiency Comparison for Various Plastic Honeycombs in Flat Black Collectors
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- Figure 7. Efficiency of Honeycomb in Selective Black Collectors
- Figure 8. Comparison of Diurnal Energy Collected by Honeycomb and Nonhoneycomb Collectors

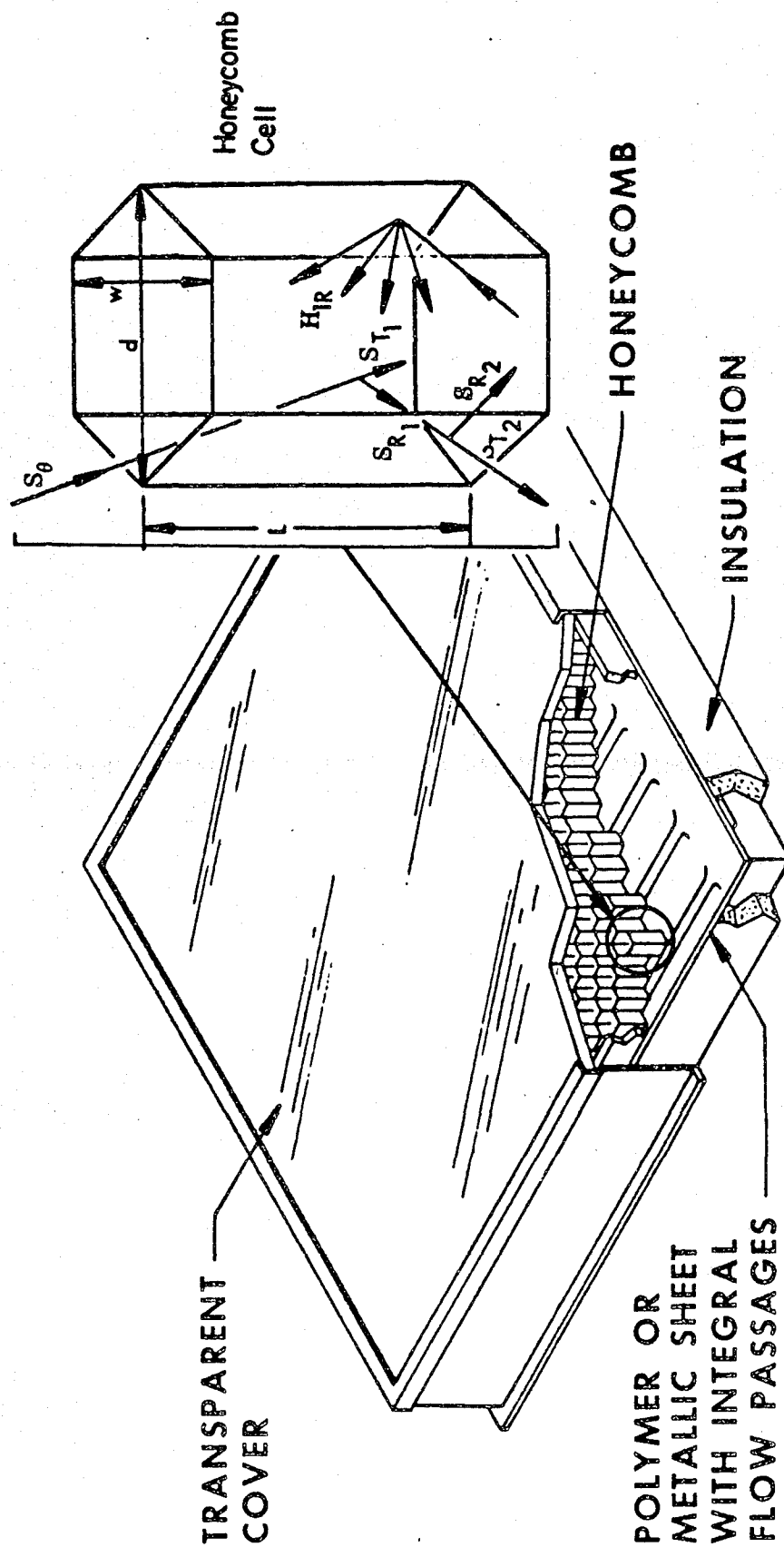
Table I
TRANSPARENT PLASTIC HONEYCOMBS STUDIED

MATERIAL	CELL DIA.		FILM THICKNESS		ASPECT RATIO
	(cm)	(in.)	(mm)	(in.)	
LEXAN	0.476	3/16	0.076	0.003	2 → 10
LEXAN	0.953	3/8	0.076	0.003	1 → 5
MYLAR	0.953	3/8	0.076	0.003	1 → 5
TEDLAR	0.953	3/8	0.102	0.004	1 → 5
KAPTON	0.953	3/8	0.025	0.001	1 → 5

Table II
SINGLE FILM OPTICAL PROPERTIES

MATERIAL	FILM THICKNESS (mm)	SOLAR SPECTRUM			INFRARED SPECTRUM		
		τ_s	ρ_s	α_s	τ_{IR}	ρ_{IR}	$\alpha_{IR} = \epsilon_{IR}$
LEXAN (TYPE 8073-112)	0.076	0.91	0.09	0	0.52	0.09	0.39
MYLAR (TYPE S)	0.076	0.86	0.12	0.02	0.33	0.11	0.56
TEDLAR (TYPE BG20TR)	0.102	0.90	0.08	0.02	0.33	0.08	0.59
KAPTON	0.025	0.69	0.12	0.19	0.46	0.12	0.42

HONEYCOMB COVERED FLAT PLATE COLLECTOR DESIGN CONCEPT



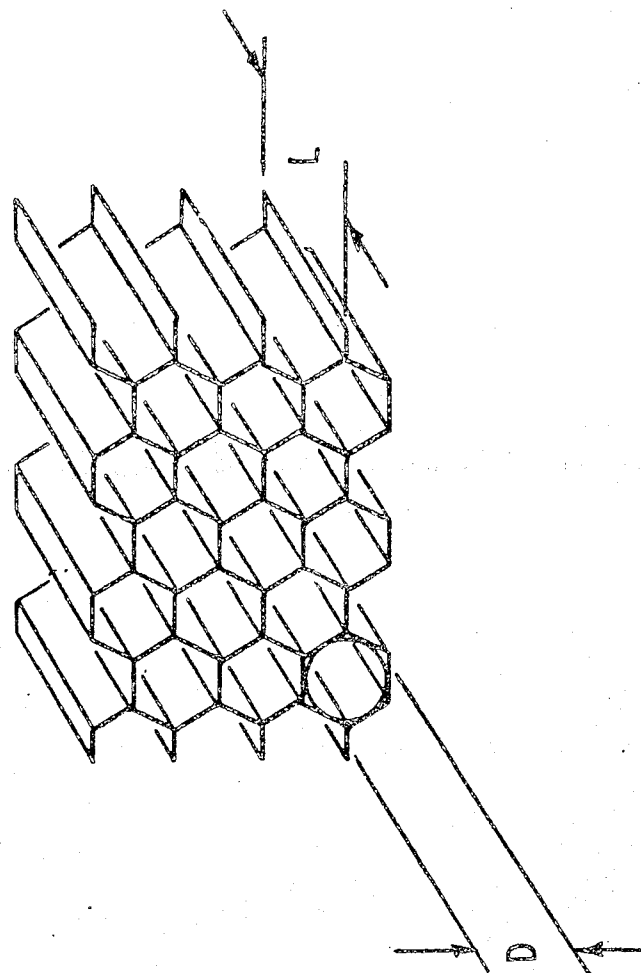


Fig. 2

Fig. 3 EFFICIENCY COMPARISON FOR VARIOUS
PLASTIC HONEYCOMBS OVER FLAT BLACK ABSORBER

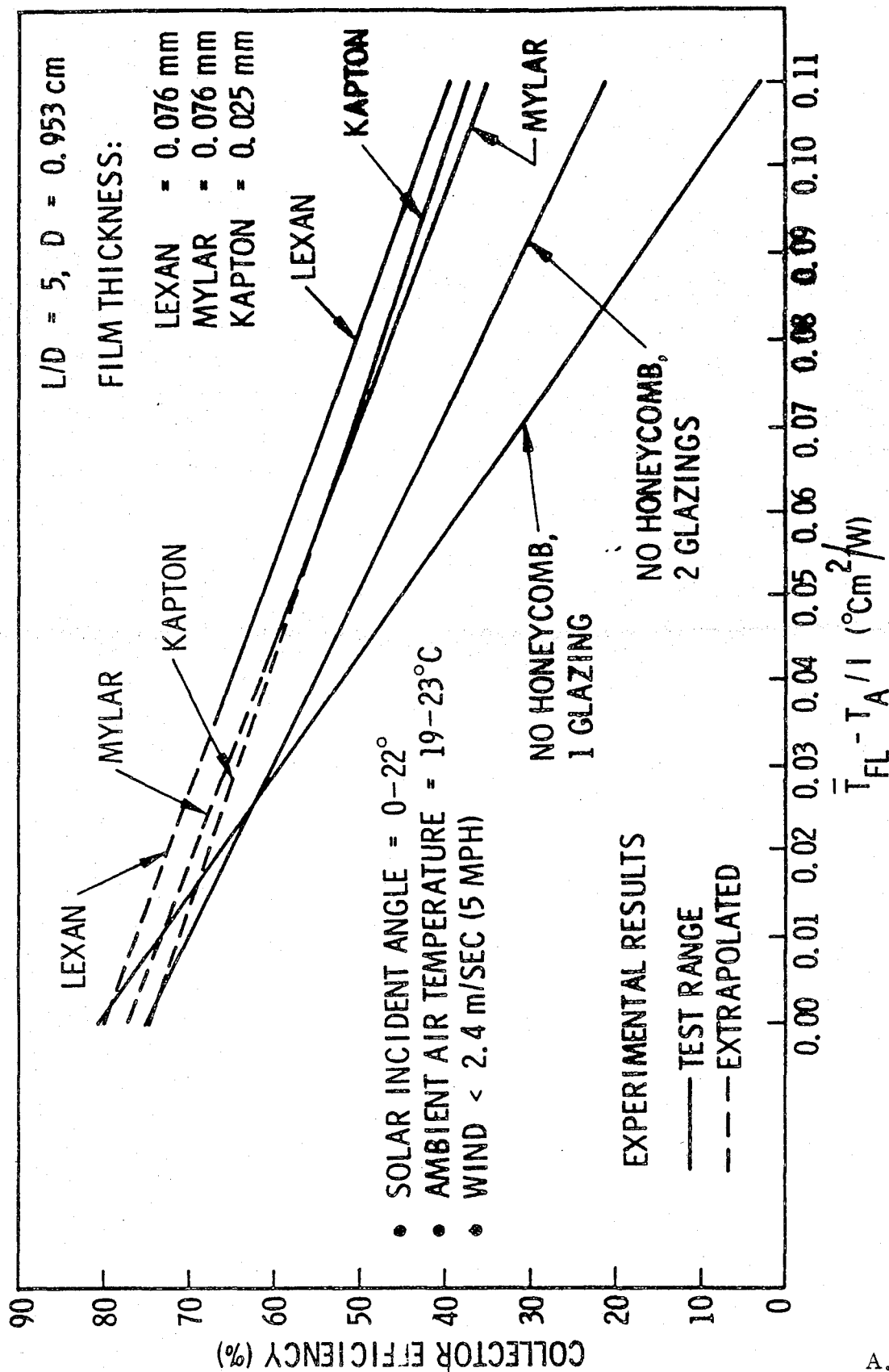


Fig. 4 DIURNAL PERFORMANCE OF VARIOUS PLASTIC HONEYCOMB, FLAT BLACK ABSORBER COLLECTORS

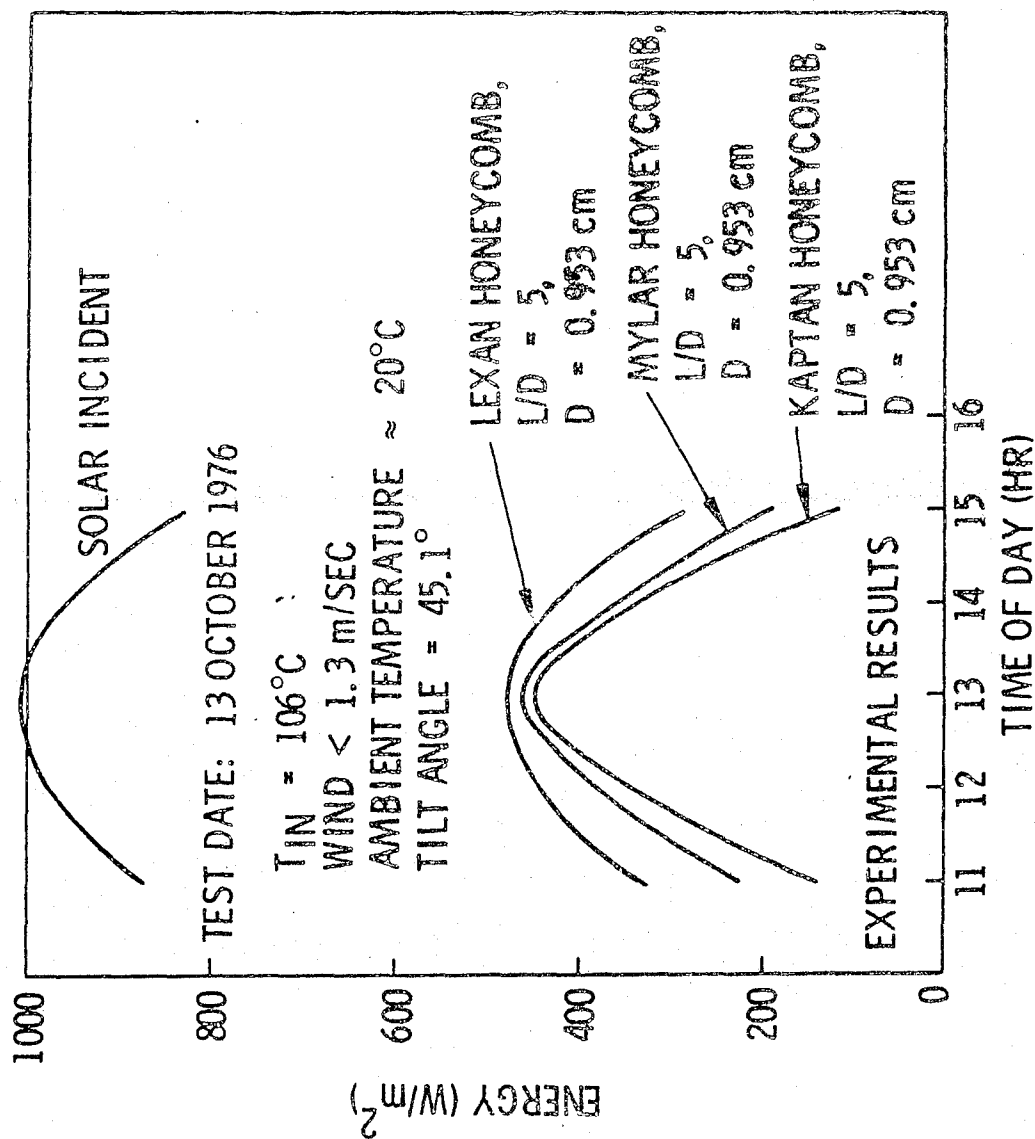


Fig.5 ASPECT RATIO INFLUENCE OF EFFICIENCY OF LEXAN HONEYCOMB COLLECTORS OVER
FLAT BLACK ABSORBER

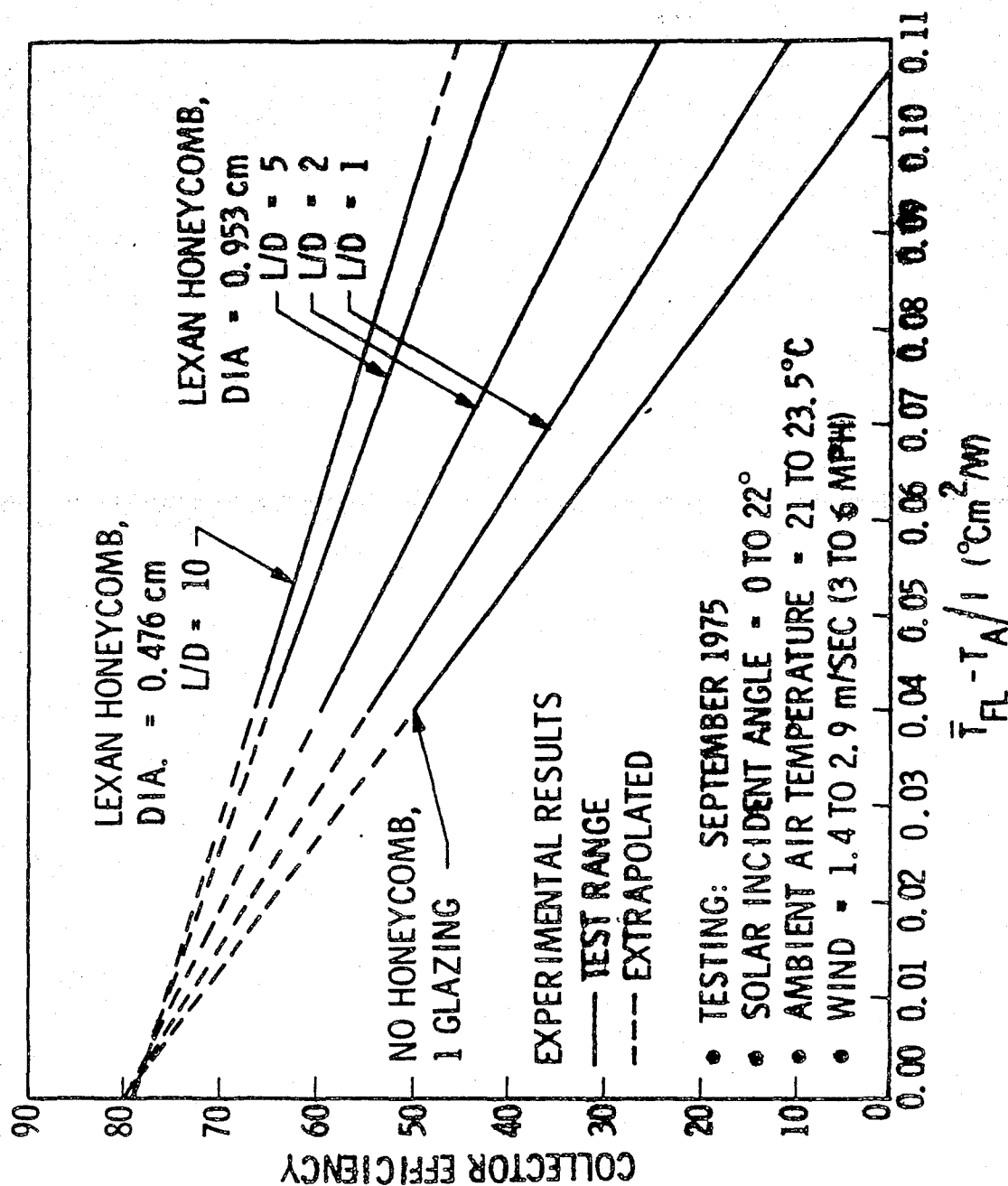


Fig. 6 DIURNAL PERFORMANCE COMPARISON OF LEXAN HONEYCOMB AND NONHONEYCOMB
FLAT BLACK COLLECTORS

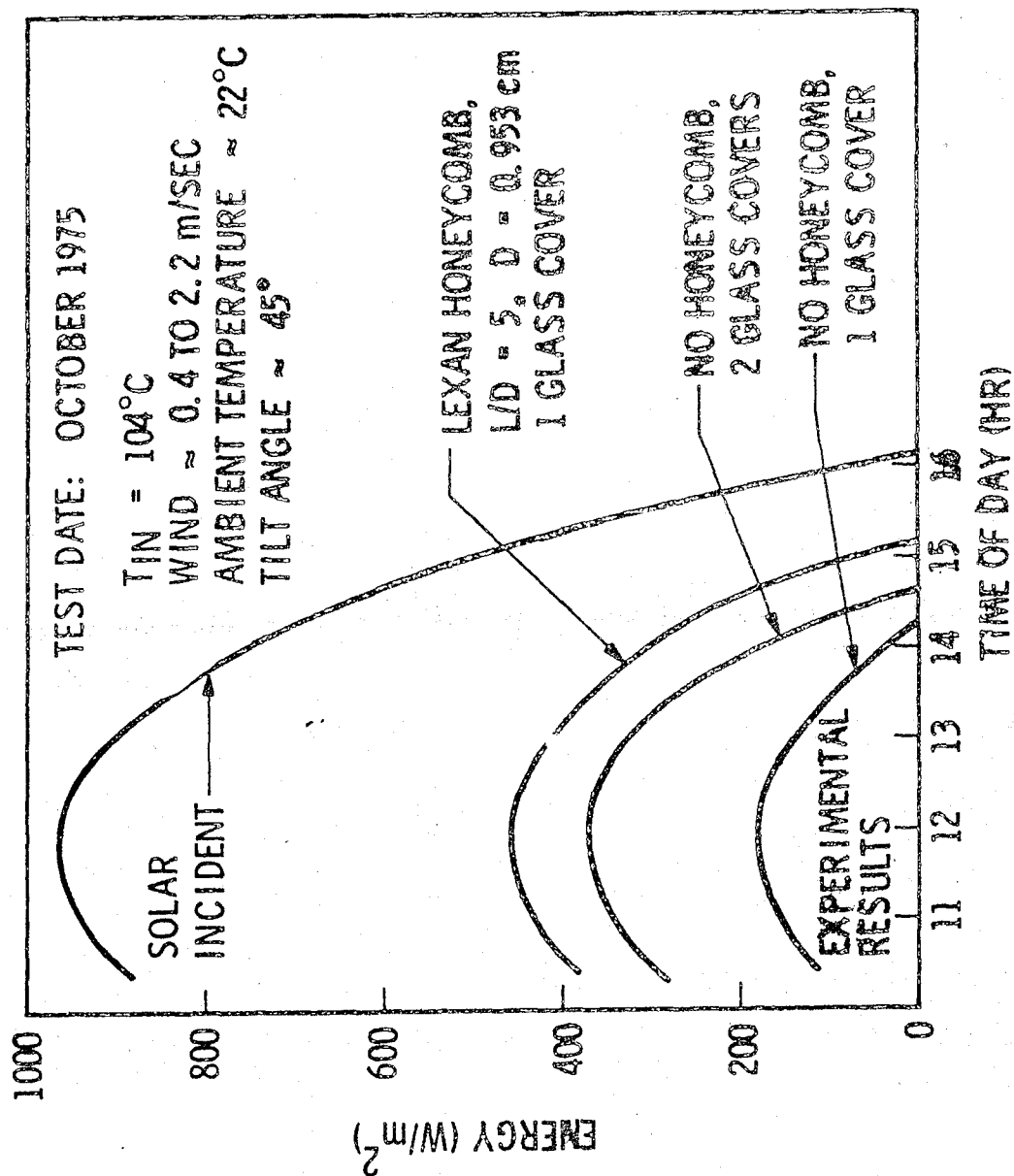


Fig. 7 EFFICIENCY OF LEXAN HONEYCOMB COLLECTORS
WITH SELECTIVE BLACK ABSORBERS

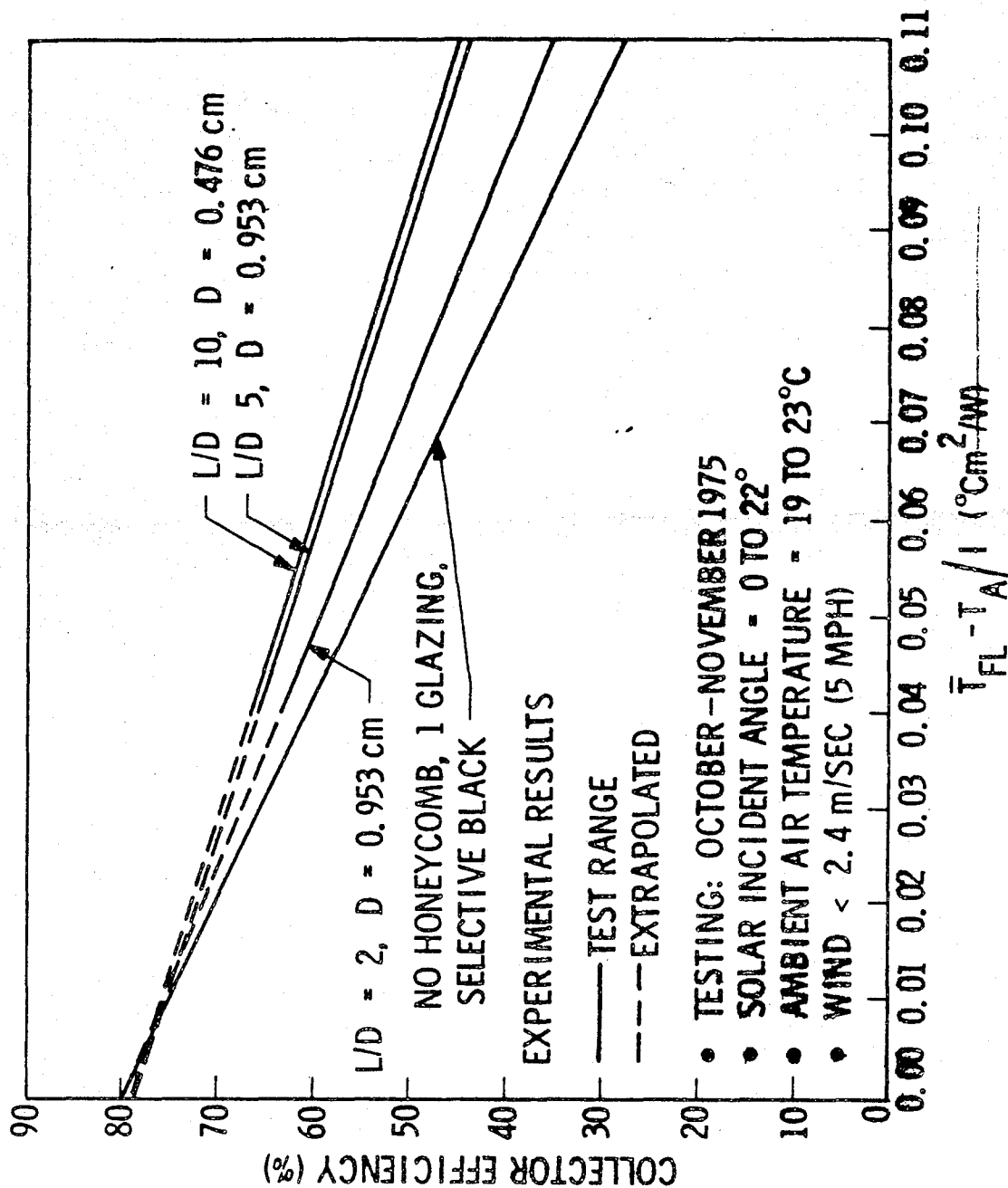
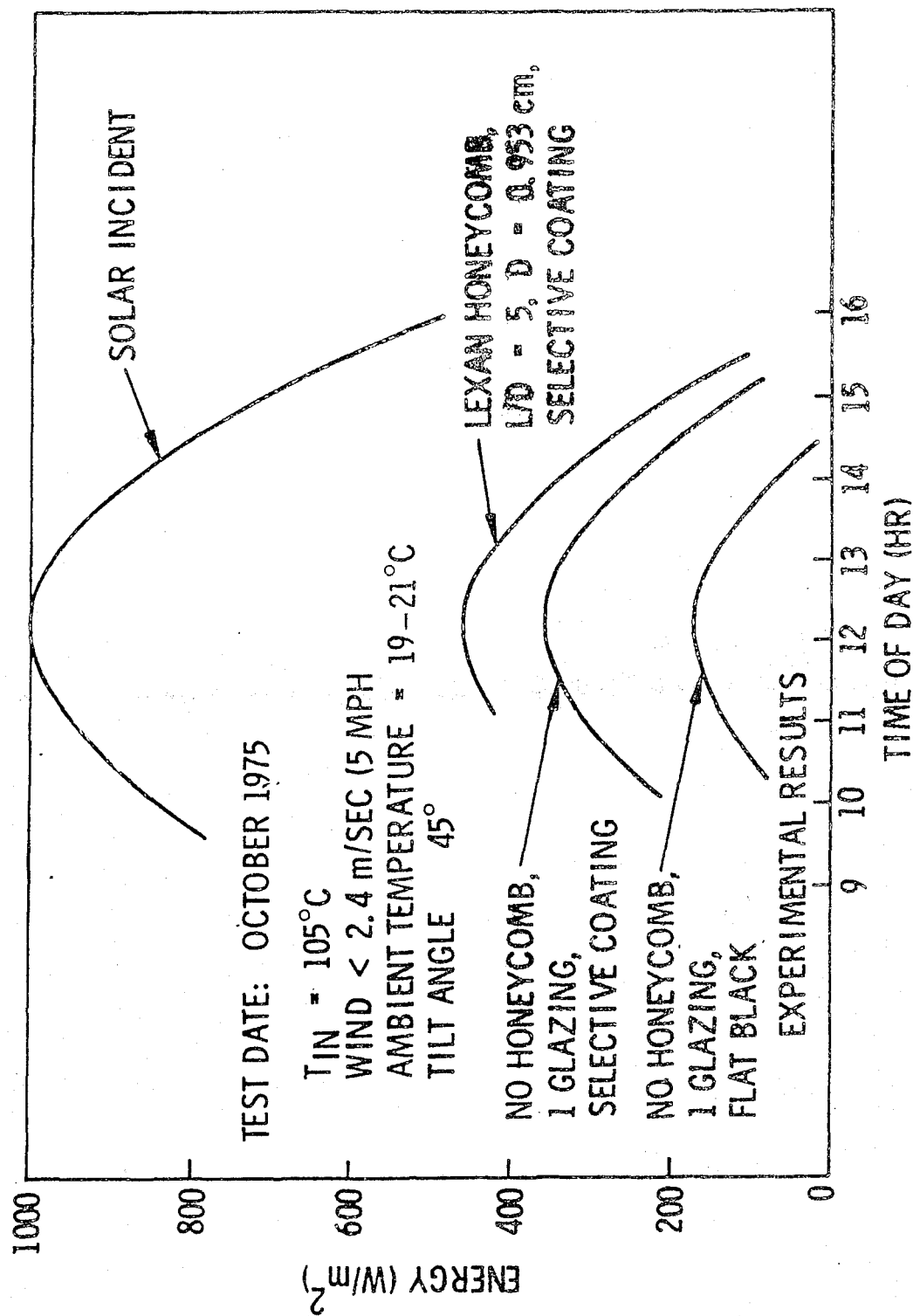


Fig. 8 COMPARISON OF DIURNAL ENERGY COLLECTED BY HONEYCOMB AND NONHONEYCOMB COLLECTORS



A.2 ECONOMIC STUDIES OF PLASTIC HONEYCOMB
SOLAR COLLECTORS

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ECONOMIC STUDIES OF PLASTIC HONEYCOMB SOLAR COLLECTORS

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ABSTRACT

Performance and cost data are presented for various flat-plate solar collectors, including those with Lexan honeycomb. A comparison is made between the efficiencies and costs of the various designs. A relative cost analysis shows the most effective collector for different temperature regions. The analyses show that collectors equipped with Lexan honeycomb are more cost effective than comparable nonhoneycomb collectors when operating at temperatures greater than 108°F above the ambient.

INTRODUCTION

The need for development of low-cost solar collectors with improved efficiency at the higher temperatures required for both heating and cooling of buildings has led researchers to consider placing a transparent honeycomb structure between the absorber plate and transparent cover to reduce the reradiation and convection losses (1,2). Initial experimental studies by Cunningham and Streed (3) with Mylar honeycomb demonstrated the potential for transparent plastic honeycomb to increase collector efficiency. Recent work performed by Hollands (4) and by Baldwin, et al. (5) has shown that convection heat loss from the collector can be suppressed through the use of properly designed honeycomb. In addition, experimental studies by Buchberg and Edwards (6) on glass honeycomb and by Marshall, et al. (7) on plastic honeycomb have shown that the reradiation losses from collectors with flat black absorbers are reduced by using honeycomb structures. Testing of a full-scale collector containing Lexan honeycomb (7) verified that honeycombs increase collector efficiency. Also, recent data (8) indicate that Lexan honeycomb gives the best performance of the low-temperature plastic honeycombs. However, very little information has been reported on the cost effectiveness of honeycomb collectors, especially for those containing plastic honeycomb. Consequently, a cost analysis was made to

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compare plastic honeycomb and nonhoneycomb collectors using the latest prices received from honeycomb manufacturers.

DISCUSSION

The economic studies were based on the cost to collect and retain a given amount of solar energy. An area of present confusion in reporting solar collector costs is that of giving the collector cost on a per area basis only, with little or no reference to efficiency or applicable operating temperature range. The potential user then has to refer to efficiency curves to determine a collector's real cost effectiveness in relation to other collectors. In these studies both collector performance (i.e. efficiency) and cost per unit area including installation costs were combined to determine the collector's relative cost. A baseline collector was selected for reference purposes, and the relative costs of various other collector designs were compared to the reference collector.

In order to obtain a collector's relative cost, both the cost per unit area and efficiency of the collector must be known. The relative cost of a particular design is then calculated from

$$RC = (C/\eta) / (C/\eta)_{\text{reference collector}}$$

where

RC = Relative Cost

η = Efficiency of Solar Collector

C = Cost of Collector per unit area

This expression relates the cost of energy collected by a particular collector to the cost of energy collected by a baseline reference collector. When a collector's relative cost figure is less than one, this means it will supply more useful energy per dollar expended than the reference collector. Therefore, this equation considers the fact that a more expensive, but more efficient collector, can actually cost the user less than a cheaper, less efficient collector for a given system's application.

Performance

The efficiencies were obtained from experimental data where available and by analysis where experimental results were lacking. The analysis used the Lockheed solar computer program SOLAR. This program has been used for many parametric studies involving collectors. The program handles up to five cover plates and has analyzed a wide variety of designs, including honeycomb collectors, evacuated collectors, and those having covers which are partially transparent in the IR spectrum. Inputs to the program consist of weather and solar data, the fluid inlet and backside of insulation temperatures, the collector orientation and its physical properties and dimensions, the fluid flow conditions,

and cost data. The program calculates component temperatures, collector efficiency, and relative cost, and displays this information as well as a detailed heat map of the collector elements as the output.

The experimental data was obtained at the Lockheed Solar Collector Test Facility which is described in Ref. 7. The tests were performed per NBS standards (9). The test collectors were constructed using a 17" x 50" Roll Bond aluminum absorber panel. The glazings were water white glass by Fourco having a solar transmission of 85%. Both flat black and selective black absorber plate coatings were used. The flat black had a solar absorptance of 0.95 and an emittance of 0.9. The selective coating had a solar absorptance of 0.95 and an emittance of 0.18. The Lexan honeycomb cell size was 0.375" in diameter by 1.875" long giving an L/D of 5.

The performance given in this paper for most of the collectors is based on experimental data. Computer predictions of efficiency were necessarily made for the two-cover glass design since no testing was done with this solar collector. Previous comparisons between measured and predicted performances of nonhoneycomb collectors have agreed very well so these calculations are believed appropriate for this study.

Cost Data

Costs were obtained for the various collector designs listed below:

Collector Designs Analyzed

Absorber Plate Coating	Honeycomb	No. of Covers
*Selective Black	No	1
Selective Black	No	2
Selective Black	Yes	1
Flat Black	No	1
Flat Black	No	2
Flat Black	Yes	1

*Baseline Reference Collector

A typical cost to the consumer was selected for the baseline reference collector based on the cost of a commercially available collector from Chamberlain Manufacturing, Inc. (10). The costs to the consumer for the various collectors considered are given in Table 1 and include the material, labor, overhead and profit. Installation costs are not included in Table 1.

It must be recognized that collector and component prices are continually changing. However, the numbers used were obtained from various suppliers and represent reasonable prices as of February 1977.

RESULTS

Performance

The performance of the various collector designs studied are shown in Figures 1-4. Fig. 1 shows the efficiencies of the various flat black designs, while Fig. 2 gives results for the selective black designs tested per NBS standards near solar noon. For both coatings the Lexan honeycomb design is the most efficient over the entire temperature range. The flat black absorber/one-glass cover/no honeycomb collector efficiency decreases drastically with increasing temperature and above 120°F is the least efficient collector of those shown. However, with a selective black absorber the single-glazed and double-glazed designs are very close in efficiency. At lower temperatures the double-glazed selective-coated collector is less efficient than the single-glazed because of the additional transmission losses through the second cover. At high temperatures the double-glazed collector is more efficient than the single-glazed since its transmittance losses are offset by the decrease in convection and radiation losses.

In calculating the cost effectiveness of collectors the diurnal energy collected by the various collectors is of prime importance. The useful energy collected over a daily period is the amount available to the user. The required collector area is based on this energy total. Figures 3 and 4 are diurnal plots for collectors operating at 220°F; they show that as the sun moves from its solar noon position, the efficiencies of nonhoneycomb collectors decrease much more rapidly than the Lexan honeycomb collector. This result is expected since the Lexan honeycomb has a very high solar transmission over a wide range of solar incident angles. Comparing Figures 1 and 2 to Figures 3 and 4, it can be seen that using collector efficiencies near solar noon for cost-effective analyses gives conservative results when presenting the cost advantages of honeycomb collectors compared to nonhoneycomb collectors.

Relative Cost

The relative costs for the various collector designs (using efficiencies from Figures 1 and 2) are shown in Fig. 5. From these results the following observations are made:

- The most cost-effective design at low operating temperatures ($\Delta T < 60^\circ\text{F}$) is that with flat black, single glazing, and no honeycomb.

- The most cost-effective design at high operating temperatures ($\Delta T > 135^{\circ}\text{F}$) is that with selective black, Lexan honeycomb, and a single cover.
- Between $\Delta T = 60^{\circ}\text{F}$ and $\Delta T = 108^{\circ}\text{F}$ the most cost-effective design is one with a selective coating, single glazing, and no honeycomb.
- The collector with a flat black coating, single glazing and Lexan honeycomb is more cost effective than one with a selective coating, single glazing and no honeycomb above $\Delta T = 108^{\circ}\text{F}$.
- For operation at both medium and high temperatures the collector with the best overall cost effectiveness is one with a flat black coating, single glazing, and Lexan honeycomb.
- Two designs which are not cost effective are the double - glass glazed collectors with either flat or selective black coatings.

The variation of relative cost with temperature for some of the collector designs is appreciable. The least expensive design (single-glazed, flat black, no honeycomb) has the lowest relative cost at the low temperature where the efficiencies of all the single-glazed designs are nearly equal. However, as the collector temperature increases, the heat losses for this design increase rapidly, causing the efficiency to decrease and the relative cost to increase drastically (at a ΔT of 170°F its relative cost is \$4.45). For the Lexan honeycomb collector the opposite trend takes place. Being the most expensive collector, its relative cost is high at low temperatures. At high temperatures the honeycomb has suppressed the heat losses sufficiently so that the efficiency is still high causing the relative cost to decrease.

Another measure of collector usefulness is the area required to supply a specific amount of energy. The diurnal results of Figures 3 and 4 were integrated to obtain the energy collected over a day and were combined with the cost data of Table 1. The cost comparison is given in Table 2 for collectors supplying 4 therms of energy per day at a collector operating temperature of $\Delta T = 150^{\circ}\text{F}$. As was the case with relative costs, the Lexan honeycomb/single-glazed/ selective black design is the least expensive. For other operating temperature ranges, another design may be the most cost effective.

CONCLUSIONS

An economic analysis was completed to compare the cost effectiveness of honeycomb and nonhoneycomb solar collectors. This study emphasizes the importance of selecting the collector design based on the job to be done and the temperature range expected for

collector operation. The analysis showed that the least costly collector design may not be the most cost effective when integrated into the overall system. Conversely, the most expensive collector on a per unit area basis may be the most cost effective for a specific system application. From the results presented herein the following specific conclusions can be stated for the honeycomb and nonhoneycomb collectors analyzed:

- For operation at both medium and high temperatures, the most cost-effective collector design is that which has Lexan honeycomb, flat black coating, and single glazing.
- For high temperature operation only, the Lexan honeycomb, selective black coating, single-glazing collector is the most cost effective.
- The collector with no honeycomb, flat black coating, and single glazing is most cost effective at low operating temperatures. At high operating temperatures it has a very poor cost effectiveness because of its low efficiency.
- Flat black or selective black coated collectors with double glazings are not cost effective anywhere within the wide temperature range considered in this analysis.

ACKNOWLEDGEMENTS

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TABLE 1
COSTS OF VARIOUS SOLAR COLLECTOR DESIGNS

NO. OF GLASS COVERS	COATING TYPE	HONEYCOMB	HONEYCOMB COST (\$/ft ²)	COST \$/ft ² (a)
1	BLACK CHROME	NO	-	\$13.50(b)
1	FLAT BLACK	NO	-	11.67
2	BLACK CHROME	NO	-	15.50
2	FLAT BLACK	NO	-	13.67
1	BLACK CHROME	LEXAN	\$1.50	15.75
1	FLAT BLACK	LEXAN	1.50	13.92
1	BLACK CHROME	MYLAR	1.05	15.08
1	FLAT BLACK	MYLAR	1.05	13.25

(a) COST BASED ON APERTURE AREA.

(b) BASELINE COLLECTOR.

(OVERHEAD, G&A, AND PROFIT FACTOR = 1.5).

TABLE 2
COLLECTOR AREA AND COST REQUIREMENTS TO SUPPLY 4 THERMS OF ENERGY
PER DAY FOR COLLECTORS OPERATING AT A ΔT OF 150°F

GLASS COVERS	TYPE OF COLLECTOR		AREA REQUIRED TO COLLECT 4 THERMS/DAY (ft ²)	BASE COLLECTOR COST TO COLLECT 4 THERMS/DAY	COLLECTOR INSTALLATION COST BASED ON \$4.50/ft ²	TOTAL COLLECTOR COST	DIFFERENCE FROM BASELINE COLLECTOR COST
	ABSORBER COATING	HONEYCOMB					
1	SELECTIVE	NO	662	\$ 8,150	\$2,979	\$11,129	0
1	FLAT BLACK	NO	1,575	18,390	7,088	25,478	+ \$14,349
2	FLAT BLACK	NO	803	10,860	3,614	14,474	+ 3,345
1	SELECTIVE	LEXAN	483	7,600	2,174	9,774	- 1,355
1	FLAT BLACK	LEXAN	597	8,490	2,687	11,177	+ 48

NOTES:

1. AREAS AND COSTS ARE BASED ON DIURNAL COLLECTOR PERFORMANCE.
2. COLLECTOR OPERATING TEMPERATURE = 150°F ABOVE AMBIENT TEMPERATURE.
3. LEXAN HONEYCOMB HAS L/D = 5, D = 3/8 IN.
4. FLAT BLACK COATING $\alpha_s/\epsilon = 0.95/0.92$
5. SELECTIVE BLACK COATING $\alpha_s/\epsilon = 0.95/0.18$.
6. TRANSPORTATION COSTS ARE NOT INCLUDED.
7. INSTALLATION COSTS ASSUME EXTERNAL MANIFOLDING REQUIRED.

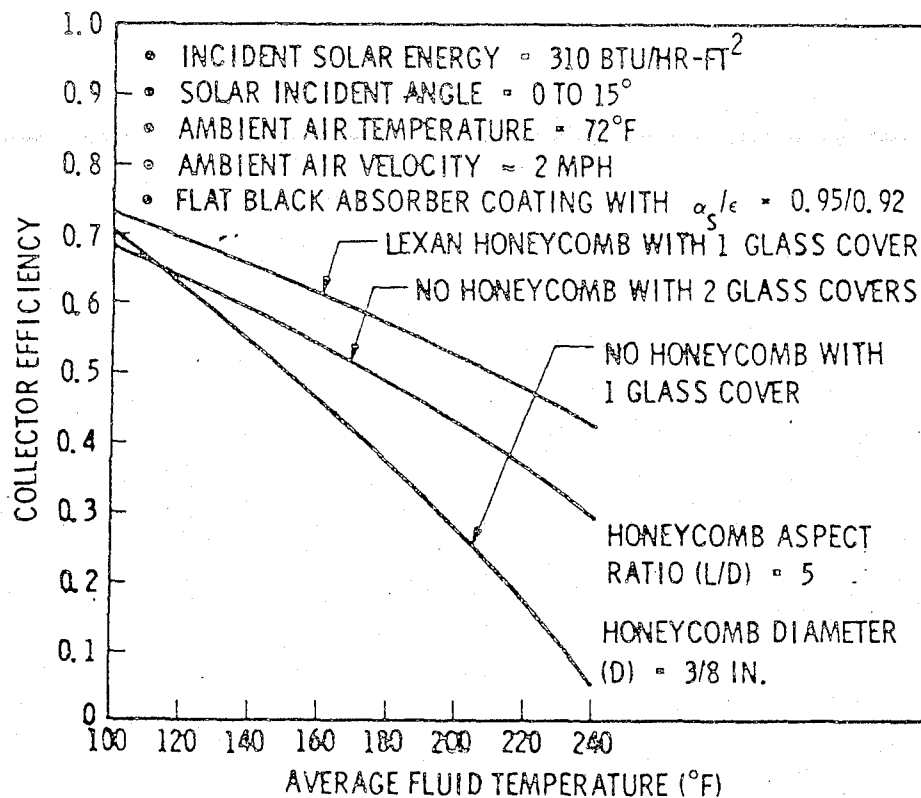


FIGURE 1
EFFICIENCY OF COLLECTORS WITH FLAT BLACK ABSORBERS

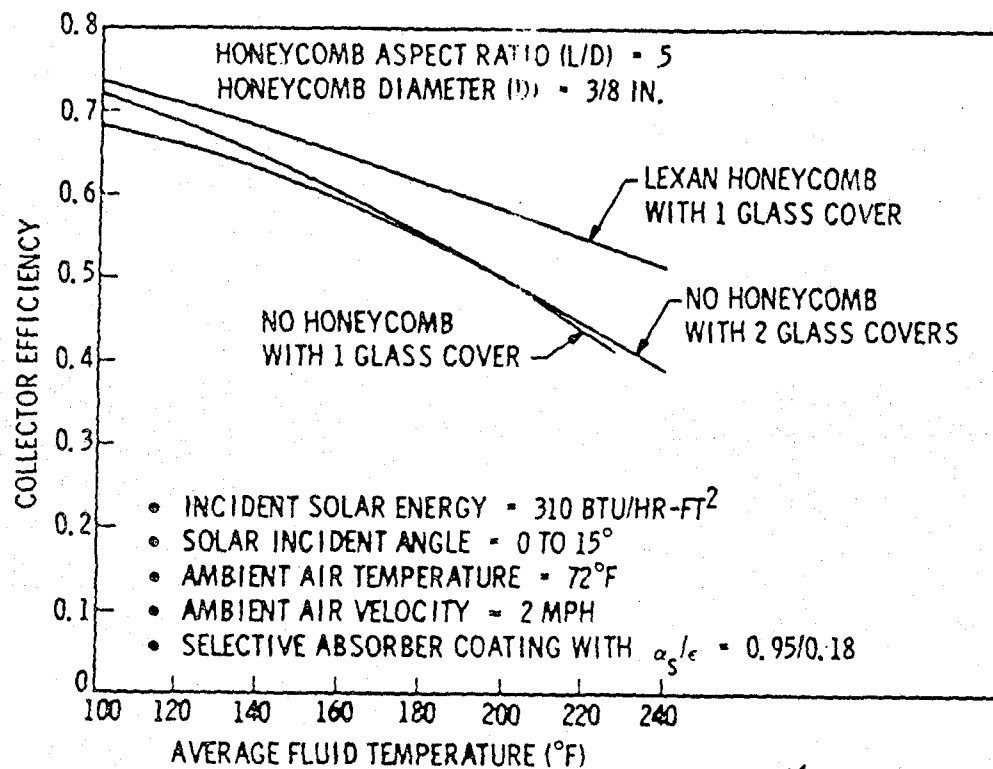


FIGURE 2
EFFICIENCY OF COLLECTORS WITH SELECTIVE BLACK ABSORBERS

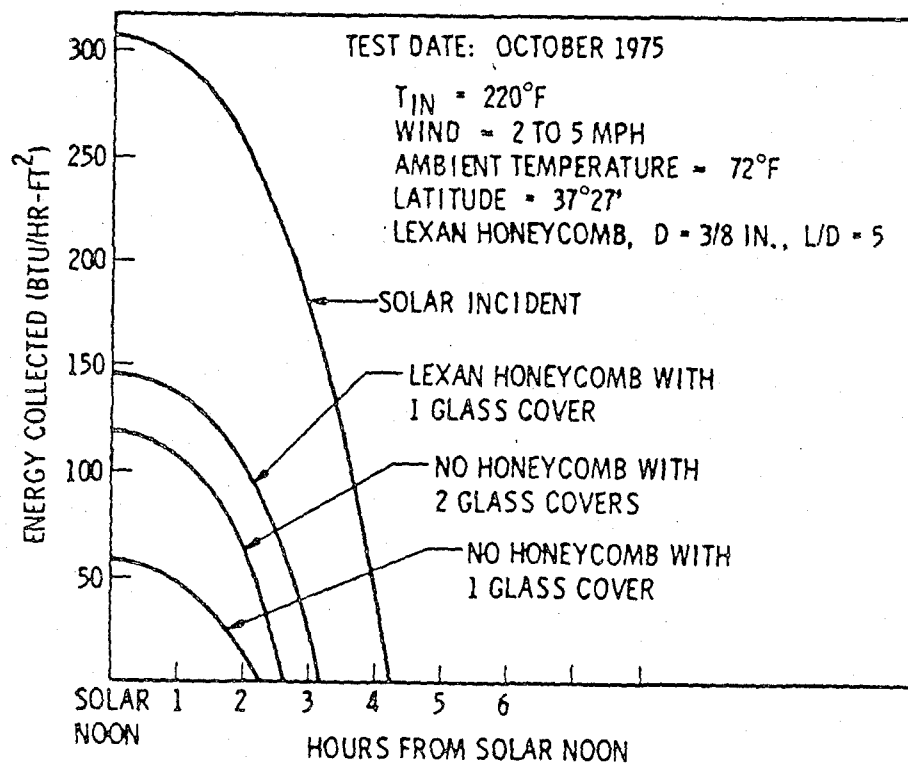


FIGURE 3
DIURNAL ENERGY COLLECTED BY HONEYCOMB AND NON-HONEYCOMB COLLECTORS WITH FLAT BLACK ABSORBERS

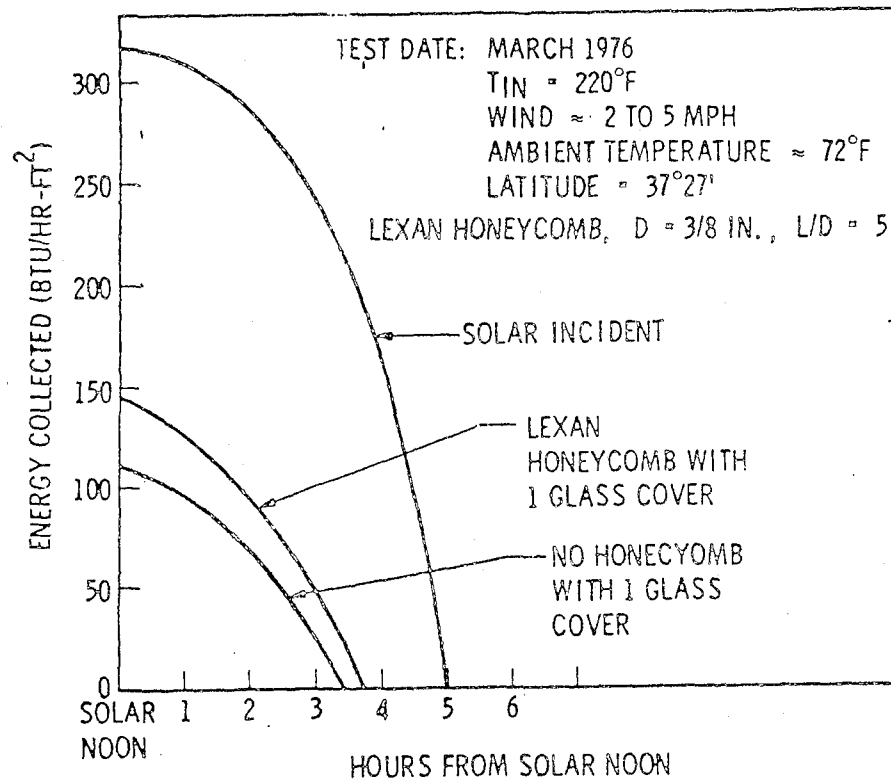


FIGURE 4
 DIURNAL ENERGY COLLECTED BY HONEYCOMB AND NON-HONEYCOMB COLLECTORS
 WITH SELECTIVE BLACK ABSORBERS

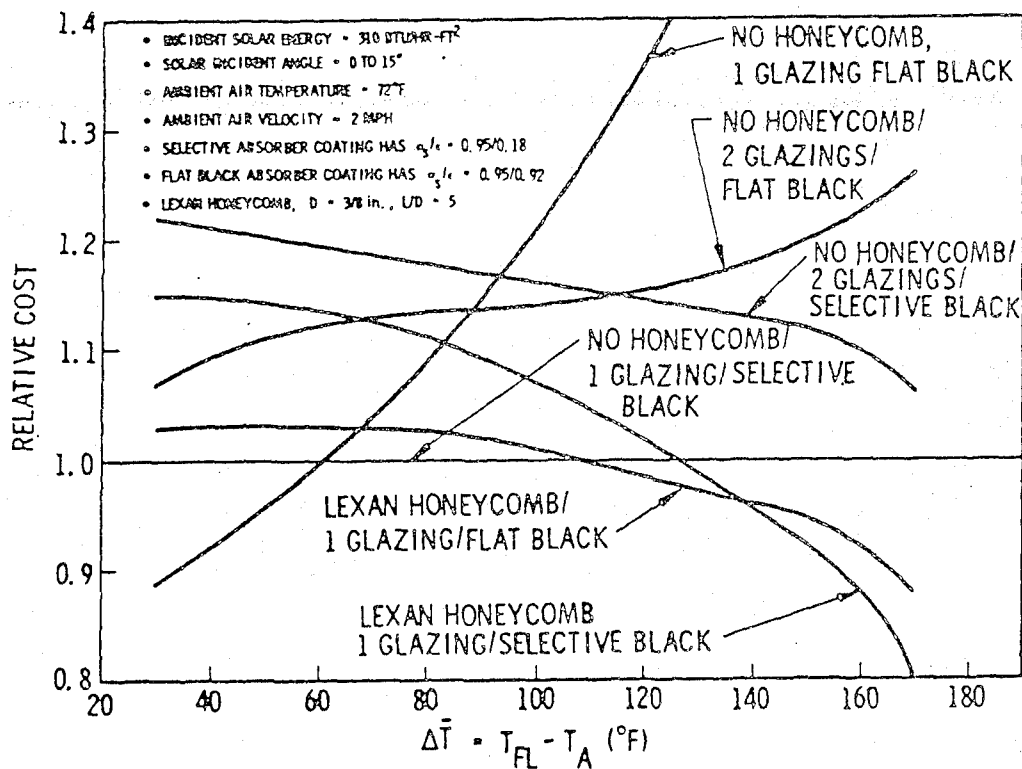


FIGURE 5
 RELATIVE COST COMPARISON FOR VARIOUS HONEYCOMB AND NON-HONEYCOMB COLLECTORS
 (BASED ON INSTANTANEOUS EFFICIENCY NEAR SOLAR NOON)

A.3 A DETAILED MODEL OF FLAT PLATE
SOLAR COLLECTOR

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A DETAILED MODEL OF FLAT PLATE SOLAR COLLECTORS

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ABSTRACT

This paper presents the details of a computer model which determines the performance of flat plate solar collectors. The program analyzes all types of flat plate collectors, including those with honeycomb between surfaces, with both performance and a relative cost of a collector design determined. Predicted performance is compared to measured solar collector efficiencies.

INTRODUCTION

A number of computer programs exist which incorporate a solar collector into an overall systems analysis; however, most of these programs do not go into fine detail in the collector analysis. Rather, they use a general equation with a loss coefficient, effective solar absorptance, and heat removal factor to obtain collector efficiency for use in an overall system analysis. In the computer program named SOLAR, described in this paper, the details of a solar collector design are considered.

With the SOLAR program the details of a collector's energy balance are displayed in a heat map. This energy flow diagram displays areas where design improvements can be made. With this technique an optimum collector design (as defined by the designer) can be obtained. The program calculates the amount of solar energy absorbed and the long wavelength energy radiation, considering multiple reflections in both calculations, and the various absorber plate effectiveness factor. For the covers the solar absorptance, reflectance, and transmittance for both solar and long wavelength energy considering multiple reflections are determined. Also, designs utilizing honeycomb materials are analyzed with the honeycomb's effect on both radiation and convection considered. The output includes the collector heat removal factor, efficiency, and a relative cost term.

* Detailed information on honeycomb solar collectors are available elsewhere.(1) In brief, glass, or plastic honeycombs, with high solar transmission are placed between an absorber plate and cover; a properly designed honeycomb suppresses convection heat transfer and decreases radiation heat losses thereby increasing collector performance compared to non-honeycomb collectors.

SOLAR is used for parametric studies in which the optical properties, tube spacing and size, weather conditions, and collector temperature, among other variables, are varied. For collectors using honeycomb the program takes the honeycomb's material properties and dimensions and determines the honeycomb's solar transmittance as well as the effect of the honeycomb on the convection and re-radiation heat losses. SOLAR also computes the relative cost of the particular design compared to a baseline collector.

The results of SOLAR are a collector's efficiency and relative cost as well as a heat map giving the component temperatures and energy distribution.

MODEL DESCRIPTION

The energy exchange mechanisms are shown in Figure 1 and are as follows:

- o Solar radiation energy to collector and covers considering absorption by the covers and absorber plate and the reflection and transmission of the covers.
- o Long wavelength (infrared) radiation exchanges between the various surfaces and to the sky considering absorber plate emissivity as well as the emission, absorption, reflection, and transmission at each cover; i.e., partially IR transparent covers are analyzed in detail.
- o Convection between the top cover and the environment as a function of the windspeed.
- o Natural convection between surfaces, including the degree of convection suppression as a function of honeycomb design.
- o Conduction through the insulation on the back of the collector.
- o Combined conduction and forced convection between the collector and the heat transfer fluid.

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Radiation

The radiation analysis is based on assuming gray body radiation properties within the solar spectrum and the long wavelength spectrum. The work of Stokes(2) was used to account for all the multiple reflections which take place.(3)

Solar Radiation

(a) Transmission of Covers

The effective solar transmission of each at the various transparent covers considering multiple reflections is calculated. Both the parallel and perpendicular components of solar radiation are used to calculate the reflectivity of each cover as a function of solar incident angle and material index of refraction. The cover's transmissivity is calculated from Bouguer's Law as a function of material thickness, extinction coefficient and solar incident angle.(4) The effective reflectance, transmittance, and absorptance of each cover are calculated considering internal reflections and transmission from the following equations:

$$\rho = r + \frac{r a^2 (1-r^2)}{(1-r^2 a^2)}$$

$$\tau = a(1-r)^2 / (1-r^2 a^2)$$

$$\alpha = 1 - \rho - \tau$$

(b) Transmission of Honeycomb

When honeycomb is used, its solar transmittance is calculated by the equation:

$$\tau_{HC} = \frac{1}{2}(1 + \tau_D)$$

The effective specular transmittance, τ_D , depends upon the number of reflections a solar photon requires to reach the absorber plate and is a function of honeycomb material, honeycomb aspect ratio, L/D , and solar incident angle.(5) The honeycomb's absorptance is set equal to zero (a reasonable assumption based on measurements for plastic honeycomb (5)) and its reflectance is then given by

$$\rho_{HC} = 1 - \tau_{HC}$$

(c) Effective Solar Absorptance

The results of Stokes are used to obtain the amount of energy absorbed by each cover and the absorber plate surface. The analysis considers multiple reflections and accounts for all energy incident upon the top cover.

Long Wavelength Radiation Exchange

The radiant energy exchange between surfaces and the sky is determined considering the infrared transmission through covers and all the reflections between the various covers and the absorber plate.

In these calculations the geometric view factor is assumed to be unity since the distance between surfaces is small compared to their area. The external radiation is to a "black sky" that is 6°C colder than the air.(4) For a honeycomb covered absorber plate an effective emittance of the absorber plate/honeycomb combination has been proven to work adequately.(1)

Convection

(a) Convection between Top Cover and Environment

The heat transfer coefficient between the top cover exposed to the ambient air is given by McAdams(6) as

$$h = 5.7 + 3.8 \cdot V$$

where h is in $W/M^2 \text{ } ^\circ K$ and V is M/S

(b) Convection between Surfaces

For a solar collector without a honeycomb intermediary, the natural convection between surfaces is given by Hollands (7) as

$$Nu = 1 + 1.41 \left(1 - \frac{1708}{Ra \cdot \cos \beta} \right) \cdot \left(1 - \frac{1708 (\sin 1.8 \beta)^{1.6}}{Ra \cdot \cos \beta} \right) + \left[\left(\frac{Ra \cos \alpha}{5830} \right)^{1/3} - 1 \right]$$

Where the bracket with a dot ()^{*} indicates that if the quantity within the brackets is negative, the quantity is made equal to zero. If honeycomb is used between surfaces, the expression for the convection(8) is

$$Nu = 1 + .89 \cos(\alpha - \beta - 60^\circ) \cdot \left[\frac{Ra}{2420(L/D)^{1/4}} \right]^{2.38 - 1.64 \sin \alpha}$$

In Reference (8) it is recommended that the equation be used for $30^\circ \leq \alpha < 90^\circ$, $L/D < 4$ and $RA/(L/D)^{1/4} < 6000$; however, the expression still gives quite accurate results over the total range of collector tilt angles and aspect ratios. Also, in the computer program if the Nusselt number calculated for honeycomb exceeds the natural convection Nusselt number by more than twenty per cent, then the natural convection Nusselt number is used. (8)

(c) Combined Conduction and Convection between Collector and Fluid

The heat transfer coefficients within the flow passages are calculated for either laminar or turbulent flow using standard forced convection in tubes equations. (9)

Insulation Losses

The conductance from the collector to the surroundings through the insulation is a program input. In so doing, three dimensional effects and edge losses can be considered in detail.

Useful Heat Gain

The useful heat removed from the absorber considers the temperature gradient in the direction of flow as well as one between tubes. The temperature distribution between tubes is analyzed using the classical fin equations, assuming a tube and sheet construction for the absorber. The fin efficiency is calculated and combined with the forced convection coefficient for the flow in the tube and the bond conductance between tube and absorber plate to obtain an overall efficiency factor per the method given in Reference (5). In considering the effect of the temperature gradient in the direction of flow, the absorber plate heat removal factor is calculated. All the factors are temperature dependent, and the mean plate temperature, defined as

$$T_M = \frac{1}{L} \int_0^L T_y dy$$

is used

Relative Cost

Relative costs are calculated and compared to a baseline collector whose cost and efficiency are input. The cost of the collector of interest is input and if honeycomb is used, honeycomb cost parameters are also input. The relative cost is calculated from the equation

$$R.C. = \left(\frac{\text{Cost}}{\text{Efficiency}} \right)_{\text{Coll.}} / \left(\frac{\text{Cost}}{\text{Efficiency}} \right)_{\text{Baseline Coll.}}$$

A relative cost less than one means the collector of interest is supplying more energy per dollar than is the baseline collector.

METHOD OF ANALYSIS

The program calculates efficiencies and temperatures for steady-state conditions. An iterative process is used in which an energy balance is performed at each cover and at the absorber plate.

Figure 2 is a flow diagram of the method of analysis. With the input data of a particular design, the cover's (or covers') single film optical properties are calculated, as well as its total solar absorptance and transmittance, considering reflections between surfaces. Next, the absorbed solar energy for each surface is calculated with the incident energy either an input or calculated for clear day data by ASHRAE methods.(10) Then all infrared radiant interchange factors are determined, including the infrared transmittance for covers when necessary. All of the above calculations are done only once, whereas the following calculations are done each iteration using the component temperatures of the previous iteration. First, the convection coefficients between covers and, from these, the convection conductances are calculated using the temperature dependent properties of air. Next, the radiation terms are linearized to obtain a radiation heat transfer coefficient. Also, the convection coefficient between the fluid and flow passages is calculated. The absorber plate fin efficiency, collector efficiency factor, and heat removal factor are calculated considering the two dimensional absorber plate temperature distribution. The useful energy removed by the fluid is then obtained.

INPUT AND OUTPUT

The computer program takes input data of the ambient air, water inlet and backside of the insulation temperatures, solar insolation, wind speed, collector orientation, and the collector's thermal properties and dimensions, relevant optical properties, and cost information. The output consists of the solar absorption and transmission of the absorber plate and covers, component temperatures, a detailed heat map of the collector elements, the collector efficiency, and relative costs.

A very useful feature of the computer printed output is the heat map. As mentioned previously, from the heat map the heat flow distribution is clearly defined and displayed so that those areas which need design improvement are easily identified.

The program is flexible so that changes in any collector component can be easily simulated and results quickly obtained.

Figure 3 is an example of the program for a honeycomb design with a partially IR transparent cover. The example is for a collector with a Tedlar cover, a plastic honeycomb, and a flat black absorber plate. (The negative value for C.G. gap, i.e. the distance from absorber plate to cover, is a flag designating a honeycomb design.) The heat map clearly displays the flow of heat and its relative distribution. Notice for the IR partially transparent cover, the absorber plate radiates directly to the sky.

CORRELATION WITH EXPERIMENTAL DATA

A large amount of flat plate collector performance data has been collected at the Lockheed Solar Collector Test Facility. A comparison between predicted and measured data are given in Figures 4 through 6. Figure 4 shows the predicted and measured efficiency for a collector with a single cover and a selective black absorber plate, as tested for the NBS Round Robin tests (11). Good agreement exists between the prediction and the data. The straight line curve fit for the NBS data requirements intersects the predictions at the extremes, implying that the straight line curve might be somewhat erroneous. Figure 5 is the result of a "zero delta temperature" test in which the average fluid temperature was kept equal to the ambient air temperature to obtain the product of $(F_R \eta)$. The prediction and the data are very close, and the measured efficiency decreases with solar incident angle as predicted. Figure 6 compares prediction and measurements for a collector with a flat black absorber with and without Lexan honeycomb. The predictions are in good agreement with the data, slightly above the measurements. The collector is a small test model, and possible edge effects difficult to analyze might be the reason for the difference.

Test data have also been collected on honeycomb/selective black designs. However, there is not good correlation with predictions. The suspected reason is a combined air conduction/radiation interchange between the absorber plate and its adjacent honeycomb. Analysis is presently being performed on this problem.

Analyses have been performed on other designs, but are not presented since they have not been tested at the Lockheed test yard.

CONCLUSIONS

An analytical model which determines the performance of flat plate solar collectors has been presented. The program was used to predict the performance of a collector with an honeycomb intermediary. The predicted efficiency agreed well with measured data for the honeycomb collector with a flat black absorber plate. The predicted efficiency for non-honeycomb designs with both flat and selective black absorber also agreed well with measurements. A honeycomb/selective black design is the only flat plate collector design which cannot yet be analyzed.

NOMENCLATURE

a	= transmissivity
D	= honeycomb cell diameter
F_R	= heat removal factor
h	= convection coefficient
L	= width of air layer
Nu	= Nusselt number for natural convective heat transfer across the air layer
r	= reflectivity
Ra	= Rayleigh number
RC	= Relative Cost
T	= temperature
T_M	= mean plate temperature
V	= wind speed
α	= absorptance
θ	= angle of collector from horizontal
ρ	= reflectance
τ	= transmittance
τ_D	= effective specular transmittance of honeycomb
τ_{HC}	= honeycomb solar transmission

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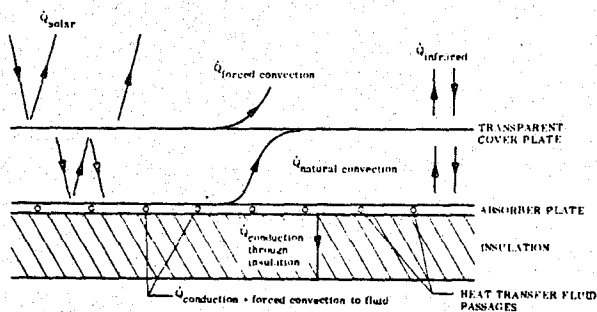


FIG. 1 ENERGY EXCHANGE MECHANISMS IN FLAT PLATE SOLAR COLLECTORS

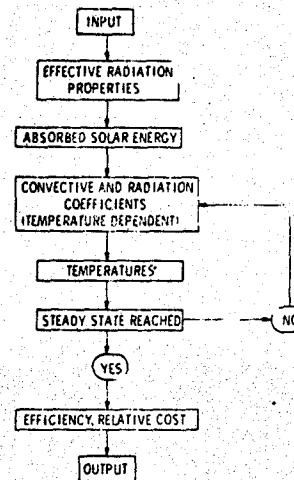


FIG. 2 FLOW DIAGRAM FOR SOLAR COMPUTER PROGRAM

```

ITEM      TEMP (DEG C)
AIR        20
INSULATION 20
WATER INLET 70
INIT COLL  73
DAILY (DA) OR SINGLE P(ESP) CALC? SP. SOLAR CONSTANT (W/SG-M)=940
TILT ANGLE=38, SUN ANGLE=30, WIND VELOCITY (MPH)=5
LENGTH (FT)=7, WIDTH (FT)=7, NO. OF COVERS=1, NO. OF TUBES=8
SINGLE PASS? NO, TUBE DIA (IN)=0.25, COLL. DELTA (IN)=0.071
BOND COND. (W/CH-K)=1000, INSULATION CONDUCTANCE (W/CH-K)=1.1
COLL. CONDUCTIVITY (W/CH-K)=1.7, FLOW RATE (GPM)=0.4
SPEC. HT. (W/SG-C)=3.5

C.      C.G. INDEX EXT. THICK-
G. ENIS REF. GAP REF. COEFF MISS
      (CH) (CH) (CH)
1. .55 .08 .74 1.48 .85 .0109
COLL ENIS=.43, ABS=.94, HONEYCOMB ASPECT RATIO=4.77
H.C. EXT. COEFF. THICKNESS=0.004, H.C. INDEX OF REF=1.54
FOR COST ANALYSIS: C1=4.70, C2=0, C4=0
SEL COATING COLL COST=7.00, SEL CTING COLL EFF=0.53

EFFECTIVE AREA= 1.991 SQ M
C.G. ABS. TRANS. ABS. TRANS.
1 .004 .894 .004 .896
COLL. .950 .896
HONEYCOMB SOLAR TRANSMISSION=.954

CONVERGE RESULTS AFTER 12 ITERATIONS

WITH AN NUMBER OF 4.24E+04, THE NUSSILT NO.= 1.048

ITEM      TEMP. HEAT MAP (WATTS)
      (DEG C)
SKY        14.0 INCIDENT SOLAR=1588.2
AIR        20.0      RADI= 179.4      RAD= 179.0
COVER 1    26.5      ABS= 9.3
      RADI= 179.4      CONDU.= 1
      RADI= 179.4      CONDU.= 1
COLLECTOR  76.0      ABS=1304.6
FLUID INLET 70.0      FLUID=179.4      EXIT TEMP= 76.2
      COND= 824.9      RADI= 179.4
      THRU= 824.9      RADI= 179.4
      INS= 824.9      RADI= 179.4
BOUNDARY  20.0
      HT REMOVAL FACTOR= .914
      EFFICIENCY= .519 FOR COLLECTOR AT 76.0 DEG C (172.2 DEG F)
      D TEMP/T= .045 W-SG M/CH
      COST OF H.C. COLL. COMPARED TO NO H.C. 1 COVER COLL= .685
  
```

FIG. 3 EXAMPLE WITH HONEYCOMB AND ONE TEDLAR COVER

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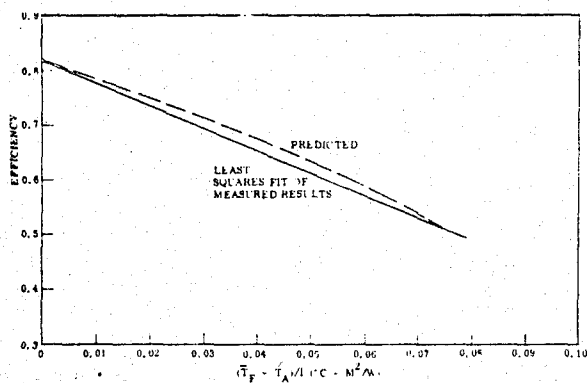


FIG. 4 EFFICIENCY OF A COLLECTOR WITH A SINGLE COVER, SELECTIVE BLACK ABSORBER

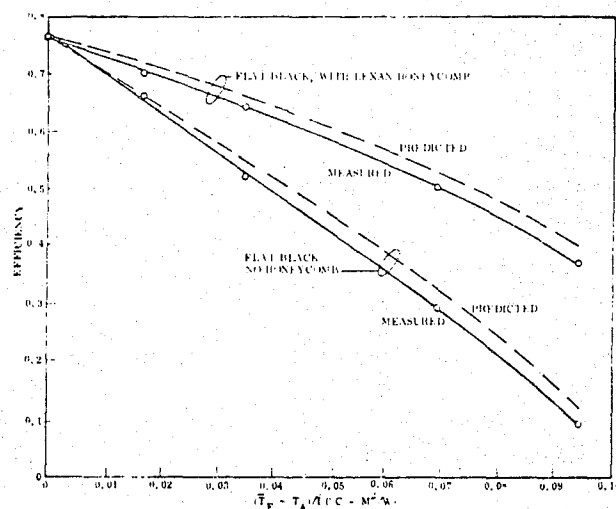


FIG. 6 COMPARISON BETWEEN MEASURED AND PREDICTED COLLECTOR EFFICIENCY WITH SINGLE COVER, FLAT BLACK ABSORBER

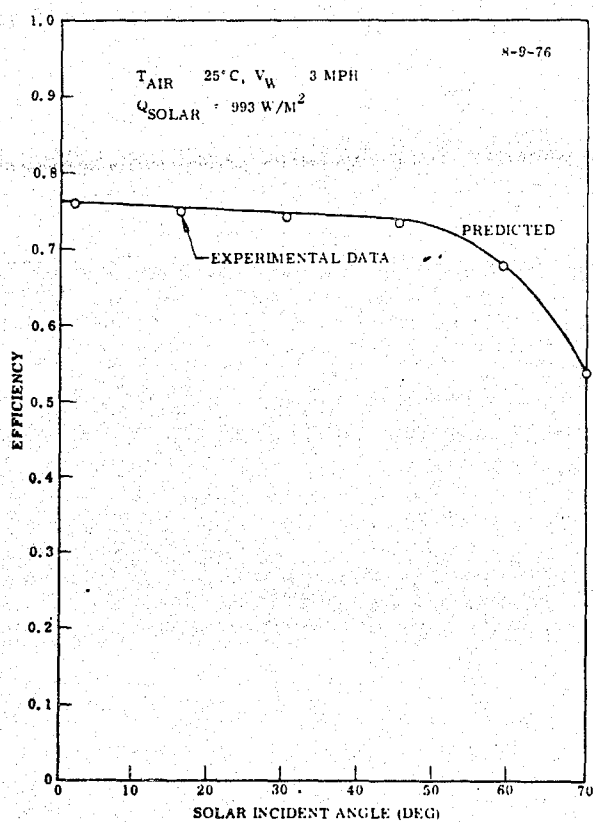


FIG. 5 SINGLE COVER FLAT BLACK COLLECTOR EFFICIENCY, AVERAGE FLUID TEMPERATURE = AMBIENT TEMPERATURE

A.4 AN APPROXIMATE EQUATION FOR PREDICTING THE SOLAR TRANSMITTANCE
OF TRANSPARENT HONEYCOMBS

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AN APPROXIMATE EQUATION FOR PREDICTING THE SOLAR TRANSMITTANCE OF TRANSPARENT HONEYCOMBS

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ABSTRACT

An approximate equation is presented for predicting the solar transmittance of transparent honeycombs. The method accounts for scattering which occurs in such honeycombs by introducing diffuse components for both the reflectivity and transmissivity of the honeycomb wall. Required inputs to the equation are the optical properties of the honeycomb wall material, averaged over the solar spectrum. Methods of determining these properties are described. Although strictly applicable to a square-celled honeycomb, the equation should be approximately valid for hexagonal honeycombs as well. The equation is compared to the measured transmittance of a hexagonal-celled Lexan honeycomb with good results.

INTRODUCTION

Recent solar test data on both plastic⁽¹⁾ and glass⁽²⁾ transparent honeycomb flat-plate solar collectors have indicated significant improvements in performance due to the use of honeycombs. Analytical methods for predicting the efficiency of these collectors prior to testing are useful for optimization and design trade-off studies. An important required element for such an analytical predictive method is the ability to predict the transmittance of the transparent honeycomb to solar radiation.

Recently Morris et al⁽³⁾ have reported such a method and applied it to glass honeycombs. Based on a Monte Carlo ray-tracing algorithm, it takes into account specular reflectance and transmission (with polarization), absorption within the glass, and scattering. Good agreement is found when compared with experiment. (A similar scheme was described by Sibbitt and Hollands⁽⁴⁾ for predicting the transmittance of a V-corrugated transparent sheet.) However, since the method is based on the Monte Carlo technique, no single equation or set of equations is given which would permit other workers to use their results directly. Moreover, it is not

always clear how their scattering coefficient is to be evaluated.

This paper presents a more approximate treatment but one which yields a single equation for the honeycomb transmittance. The method incorporates specular reflections, absorption and scattering; the polarization effect is not included, although the method could be modified to include it. Spectral variations are incorporated by use of solar averaged values of the input spectral radiation properties. A method for measuring the material scattering properties, without constructing the honeycomb, is described. Measurements of the transmittance of a plastic honeycomb as a function of the angle of incidence are reported and compared with the predictions of the theoretical equation.

MODEL

Figure 1a shows a sketch of the physical model considered. The honeycomb is assumed to be square-celled and the collimated solar radiation is assumed to have a direction parallel to the plane of one of the two sets of parallel walls which form the square-celled array.

Emission of radiation by the honeycomb walls is not of interest to the present problem, nor is the subsequent history of the solar energy which is absorbed by the honeycomb. Consequently, for the purposes of analysis, the honeycomb walls can be considered to be uniformly at zero absolute temperature. The lower face of the honeycomb ($z = 0$) is assumed to be black and also at zero absolute temperature. The top face is irradiated with solar radiation. Required is the directional transmittance of the honeycomb $T(\theta)$, defined as the irradiation on the top face divided by the irradiation on the bottom face.

A single sheet constituting the honeycomb cell wall

is modelled as having both perfectly diffuse and perfectly specular reflectivity[†] components, ρ_{ϕ}^d and ρ_{ϕ}^s respectively, with $\rho_{\phi}^d + \rho_{\phi}^s$ representing the hemispherical reflectivity. Similarly, the sheet is modelled as having both perfectly diffuse and perfectly direct transmissivity[†] components, τ_{ϕ}^d and τ_{ϕ}^s respectively, with $\tau_{\phi} = \tau_{\phi}^d + \tau_{\phi}^s$ representing the hemispherical transmissivity. The perfectly direct component represents that fraction of the incident radiation which is transmitted directly through the sheet without deviating appreciably from its original direction. This breaking down of the transmissivity into two components - one perfectly diffuse, one perfectly direct - has not to our knowledge been used before; however, it is a simple extension of the breaking down of the reflectivity into two similar components, first suggested by Seban⁽⁵⁾. These properties are functions of the polar angle of incidence of the radiation on the honeycomb, ϕ , which for the geometry considered, is related to the polar angle of incidence on the honeycomb itself by $\theta = \pi/2 - \phi$. The sheet absorptivity α_{ϕ} is of course related to the other parameters by:

$$\rho_{\phi}^d + \rho_{\phi}^s + \tau_{\phi}^s + \tau_{\phi}^d + \alpha_{\phi} = 1$$

The honeycomb wall thickness, δ , is assumed to be much less than the cell width, D , and the honeycomb height, L . Consequently, reflected and transmitted radiation can be considered to emanate from the central plane of the single sheet, whereas in fact they originate at the interfaces, or, in the case of scattered radiation, from the various points within the sheet.

ANALYSIS

Because of the repetitive nature of the square honeycomb geometry, those solar photons incident on a point on the cell wall that are directly transmitted, undergo the same subsequent history, on average, as those which are specularly reflected from the same point. Similarly, the set of photons diffusely transmitted at any given point on a cell wall, undergo the same subsequent history, on average, as photons which are diffusely reflected from the same point. Consequently, for the purposes of radiant analysis the honeycomb side-walls can be treated as being opaque, with equivalent specular component of reflectivity $\rho_{\phi,e}^s = \rho_{\phi}^s + \tau_{\phi}^s$ and with equivalent diffuse component of reflectivity $\rho_{\phi,e}^d = \tau_{\phi}^d + \rho_{\phi}^d$. The equivalent absorptivity of the side walls, $\alpha_{\phi,e} = 1 - \rho_{\phi,e}^s - \rho_{\phi,e}^d$ is the same as that for the single sheet. Since the side walls can now be treated as opaque, only a single honeycomb cell need be considered. The problem of radiant transfer through the honeycomb can now be restated in the form which is more immediately amenable to currently available methods of radiant analysis. Figure 1b shows the problem so restated. Surface 1 is a black source of

radiant energy. (All other surfaces are at zero absolute and therefore do not emit.) Surface 1 is so far removed from the honeycomb cell that radiant energy from 1 incident on 6 is uni-directional, making angle of incidence of θ on 6. (The actual distance is not important provided it is large.) Surface 6 is fully transparent. Radiation from 1 arrives at 3 directly and by reflections off 2, 4 and 7 which are opaque with specular and diffuse reflectivity components, $\rho_{\phi,e}^s$ and $\rho_{\phi,e}^d$. The transmittance of the honeycomb cell is the irradiation on 3 divided by the irradiation on 6. (Radiation exchange in such an enclosure has been treated in some detail by Edwards and Tobin⁽⁶⁾ and Edwards and Amar⁽⁷⁾. However, their solutions are for the case where the source is the top face, 6, and is black, and hence is not completely applicable, although the two problems are closely related.)

The method of analysis chosen is a zone or finite-area analysis with the zones as represented in Figure 1b. The method followed is as outlined in Ozisik^(8a), yielding ultimately the irradiation on 3. The resulting expression for the honeycomb cell transmittance is

$$T(\theta) = T_D(\theta) + \frac{\rho_{\phi,e}^d}{\rho_{\phi,e}^d + \alpha_{\phi}} \mathcal{F}_{2-3} [(1 - T_D(\theta))] \quad (1)$$

$$\text{where: } \phi = \pi/2 - \theta \quad (2)$$

$$\text{and: } T_D(\theta) = (F_{1-3}^s / F_{1-6}) \quad (3)$$

and \mathcal{F}_{2-3} is the fraction of diffuse radiation leaving \mathcal{F}_{2-3} which arrives at 3 both directly and by all possible specular and diffuse reflections. $T_D(\theta)$ is the fraction of irradiation on 6 which arrives at 3 via specular reflections only. The second term on the right hand side of equation (1) represents that fraction which arrives via paths which involve at least one diffuse reflection: $(1 - T_D(\theta))$ represents the fraction for which specular reflection does not occur on the first interface struck; $\rho_{\phi,e}^d / (\rho_{\phi,e}^d + \alpha_{\phi})$ times this gives the fraction which undergoes diffuse reflection on the first reflection; \mathcal{F}_{2-3} times this gives the fraction of this diffusely reflected radiation which arrives at the base.

By symmetry, for $\alpha_{\phi} = 0$, $\mathcal{F}_{2-3} = 1/2$. For the plastic honeycomb material and wall thicknesses of practical interest, such as Mylar, Teflon and Lexan, α_{ϕ} is very nearly zero and the assumptions $\mathcal{F}_{2-3} = 1/2$ is sufficiently accurate. The evaluation of \mathcal{F}_{2-3} for other geometries is outside of the scope of the present note, but involves straightforward radiant calculations.

The quantity $T_D(\theta)$ can be shown by specular enclosure analysis to be given by

$$T_D(\theta) = (\rho_{\phi,e}^s)^n (n+1-R) + (\rho_{\phi,e}^s)^{n+1} (R-n), \quad (4)$$

$$\text{where } R = \frac{L \tan \theta}{D} \quad (5)$$

and n is an integer which represents the lower

[†] The terms reflectivity and transmissivity are used to describe properties of the cell wall; reflectance and transmittance are used for the total honeycomb.

rounded-off value of R (e.g., if $R = 2.3$, $n = 2$, if $R = 5.999$, $n = 5$). Equation (4) is based on the fact that radiation entering the cavity from the source undergoes either n or $n+1$ reflections; $(n+1-R)$ is the fraction undergoing n reflections; $(R-n)$ is the fraction undergoing $n+1$ reflections.

Equation set (1, 2, 4 and 5) represent the recommended approximate equations for finding the transmittance of a honeycomb. Important inputs to these equations are the flat sheet properties, $\rho_{\phi,e}^s$ and $\rho_{\phi,e}^d$. Methods for their measurement will now be given through means of the example of a plastic honeycomb having walls made of sheets of .003 inch thick Lexan. Measurements of the solar transmittance of such a honeycomb are also given and will be compared to the predicted values.

DETERMINATION OF FILM PROPERTIES

Properties were measured spectrally using the Gier-Dunkle integrating sphere reflectometer essentially the same as that described in Edwards et al⁽⁹⁾. All measurements were made at normal or near-normal incidence ($\phi \approx 0$). Figure 2 shows the results. Both reflectivity measurements were made with an optical black-painted surface behind the sample Lexan film, and corrections were made for the non-zero reflectance of this backing surface. First the hemispherical reflectivity, $\rho_{\phi} = \rho_{\phi}^d + \rho_{\phi}^s$ was measured in the usual way for the apparatus, with an angle of incidence of $\phi = 10^\circ$ so that the specular component was not reflected back into the entrance port. Then the diffuse reflectivity, ρ_{ϕ}^d , was measured by setting $\phi = 0$ so that the specular component was reflected back into the entrance port. The difference between these two was assumed to give the specular reflectivity. Included in the specular component is all radiation within the solid angle subtended by the entrance port from the center of the integrating sphere, or within 0.05 steradian ($\pm 5^\circ$) of the theoretical specular path. The hemispherical transmissivity, $\tau_{\phi} = \tau_{\phi}^d + \tau_{\phi}^s$, was measured with the Lexan film sample placed at the entrance port of the integrating sphere and normal to the beam. The specular or direct-beam transmissivity τ_{ϕ}^s was measured with the sample at the entrance slit to a Perkin-Elmer Model 83 monochromator. In this measurement, all radiation striking the off-axis paraboloid collimator mirror, or all radiation transmitted within .05 steradian ($\pm 5^\circ$) of the theoretical straight path was considered to be direct-beam. The diffuse transmittance, τ_{ϕ}^d , is then determined as the difference between hemispheric and direct values. The film absorptivity was determined from $\alpha_{\phi} = 1 - \tau_{\phi} - \rho_{\phi}$.

Using the data in Figure 2, the various quantities were averaged using a weighting factor equal to the solar spectrum for air mass 2. The results were: $\rho_{\phi}^d = .012$, $\rho_{\phi} = .097$, $\tau_{\phi} = .903$, $\tau_{\phi}^s = .892$. The uncertainty in each of these values is estimated at $\pm .005$. From them, $\rho_{\phi,e}^s$, $\rho_{\phi,e}^d$ and α_{ϕ} were determined. The results were: $\rho_{\phi,e}^s = .977$, $\rho_{\phi,e}^d = .023$, $\alpha_{\phi} = 0.0$. These quantities have an estimated uncertainty of approximately $\pm .01$.

The above quantities are for normal incidence ($\phi = 0$). To convert to off-normal values (since direct measurement was not possible) it was decided to use a theoretical extrapolation, the basis for which follows. The sum of the specular transmissivity and reflectivity of a smooth sheet can be shown to be given by:

$$\rho_{\phi,e}^s = r_{\phi} + \frac{(1-r_{\phi})^2 a}{1-r_{\phi} a} \quad (6)$$

where:

$$a = \exp\left(-\frac{\gamma(k_a + k_s)\delta}{\sqrt{\gamma^2 - \sin^2 \phi}}\right) \quad (7)$$

The index of refraction, γ , of the transparent honeycomb wall material is assumed to be known. Consequently, the single-surface reflectivity, $r_{\phi}(\phi)$ is directly calculatable from the Fresnel equations for dielectrics^(8b). For the case $\phi = 0$ a measured value of $\rho_{\phi,e}^s$ is available so that the value of $(k_a + k_s)\delta$ can be found from equations (6) and (7). Once this is found, $\rho_{\phi,e}^s$ can be determined for any other ϕ using the same equation pair. Note that it has been implicitly assumed that the scattering which produces the finite values for ρ_{ϕ}^d and τ_{ϕ}^d occurs inside the film material and not at the interface itself. This is based on the observations that the direct-beam transmissivity of most of the transparent plastic films considered for honeycombs falls off rather strongly as the thickness is increased, indicating increased scattering due to the longer path length of photons in the film. The surface finish on the plastic must be smooth for the extrapolation to be valid.

In the case of the 0.00762 cm (.003 in) thick Lexan film the value of $\gamma = 1.54$ and hence $r_{\phi}(\phi = 0) = .0452$. Using a value for $\rho_{\phi,e}^s$ for $\phi = 0$ of .977 gives $(k_a + k_s)\delta = .0233$. Using these values and equation set 1, 2, 4, 5, 6, 7 and the Fresnel relations, one can now predict the transmittance of a square-celled Lexan honeycomb for any value of L/D .

MEASUREMENT OF HONEYCOMB SOLAR TRANSMITTANCE

The honeycomb chosen for solar transmittance measurements was a hexagonal-celled honeycomb having a height, L , of 4.76 cm (1.875 in) and a distance across the hexagonal flats, D , of 0.95 cm (.375 in), giving a value for the aspect ratio, L/D , of 5. The honeycomb was fabricated from the .003 inch thick Lexan sheet (whose properties were just reported), using the "Hexcel" technique, and glue joints. Full details of this honeycomb have been given elsewhere⁽¹⁾. In order to measure the transmittance of this honeycomb, two identical liquid heating solar collectors were used - one which contained the honeycomb between the glass cover and the absorber plate, called the honeycomb collector, and one which did not (called the non-honeycomb collector). The efficiency of each collector was measured simultaneously on a clear day at various times of day. The collectors were kept in a fixed position facing south so that the

angle of incidence, θ , of the direct solar radiation on the collectors (and hence on the honeycomb) varied through the day and was, therefore, different for each efficiency measurement. The angle of tilt of the collectors from horizontal was such that at solar noon the value of θ was zero. The details of the test facility used to measure the collector efficiency is given in (1). The measurements were carried out using an average liquid within a few degrees of the ambient air temperature. Under these conditions, the losses from the collector are nearly zero so that to a close approximation

$$\eta(\theta) = \tau_g(\theta) T(\theta) \alpha_p(\theta) F'$$

(This expression neglects radiation which is reflected off the plate, then reflected off the honeycomb or the glass cover and back onto the plate. Since the honeycomb and glass cover reflectances and the plate reflectance are all low, the error introduced by this should not be significant.) The quantities $\tau_g(\theta)$, $\alpha_p(\theta)$ and F' are nearly the same for each collector. Hence, if $\eta_{HC}(\theta)$ is the measured efficiency of the honeycomb collector for a given θ , and $\eta_{NHC}(\theta)$ is the efficiency of the non-honeycomb collector measured at the same time (and therefore for the same θ), then the ratio of the two must be the transmittance of the honeycomb:

$$\frac{\eta_{HC}(\theta)}{\eta_{NHC}(\theta)} = \frac{\tau_g(\theta) T(\theta) \alpha_p(\theta) F'}{\tau_g(\theta) \alpha_p(\theta) F'} = T(\theta)$$

Simultaneous measurements of $\eta_{HC}(\theta)$ and $\eta_{NHC}(\theta)$ were made at hourly intervals and the duration of each test was about 5 minutes.

RESULTS AND COMPARISON WITH THEORY

Figure 3 shows the measured collector efficiencies and honeycomb transmittance as a function of the angle of incidence, θ . Also shown on the same graph is the transmittance of a square-celled Lexan honeycomb having the same value for the ratio L/D , as predicted from the theory and film property measurements given earlier.

In light of the fact that there are substantial differences in the two geometries, the close agreement shown in Figure 3 is probably, to a certain extent, fortuitous. The measured value of $\rho_{\phi,e}^s$ at $\phi = 0$ of .977 was subject to an uncertainty of about $\pm .01$. Shown as dashed lines in the figure are the predicted transmittances if values $\rho_{\phi,e}^s$ at the extreme ends of its range were used, i.e., for values for $\rho_{\phi,e}^s$ of .967 and .987. Clearly the predicted transmittance is quite sensitive to uncertainties in $\rho_{\phi,e}^s$.

Despite this, it is concluded that the measurement technique and theory outlined here should be expected to be very useful for system optimization, interpretation of experimental results, and for the screening of candidate honeycomb materials.

NOMENCLATURE

a	= a parameter defined by equation (7).
D	= honeycomb cell hydraulic diameter.
F'	= collector efficiency factor (10).
F_{a-b}	= view factor for radiative exchange.
F_{a-b}^s	= specular view factor for radiative exchange (8c).
$s-b$	= Hottel's script F factor for radiative exchange.
k_a, k_s	= absorption and scattering coefficients of honeycomb wall material, respectively.
L	= height of honeycomb (Figure 1).
n	= an integer representing the lowest rounded-off value of R .
R	= reflection counter given by equation (5).
r	= single interface reflectivity for a smooth surface bounded by air and honeycomb wall material, when unpolarized radiation is incident at angle ϕ .
$T(\theta)$	= transmittance of honeycomb to radiation incident at angle θ .
$T_D(\theta)$	= see equation (3).
x, y, z	= co-ordinates - Figure 1.
α_ϕ	= absorptivity of honeycomb wall of thickness δ , when radiation is incident at angle ϕ .
α_p	= solar collector plate absorptivity.
γ	= index of refraction of wall material.
δ	= thickness of honeycomb wall (Figure 1).
$\eta(\theta)$	= solar collector efficiency for solar radiation at angle θ ; $\eta_{HC}(\theta)$ for honeycomb collector; $\eta_{NHC}(\theta)$ for non-honeycomb collector.
θ	= angle of incidence of solar radiation on honeycomb (Figure 1).
ϕ	= angle of incidence of solar radiation on honeycomb wall (Figure 1).
ρ_ϕ	= reflectivity of honeycomb wall for radiation incident at angle ϕ .
τ_ϕ	= transmissivity of honeycomb wall for radiation incident at angle ϕ .

Superscripts:

d	= diffuse component.
s	= specular or direct-beam component.

Subscripts:

e	= equivalent opaque value.
-----	----------------------------

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List of Figures

1. Drawings showing models of honeycomb.
2. Measured spectral reflectivity and transmissivity properties of Lexan sheet .003 inch thick for near-normal incident radiation.
3. Comparison of predicted and measured honeycomb transmittance.

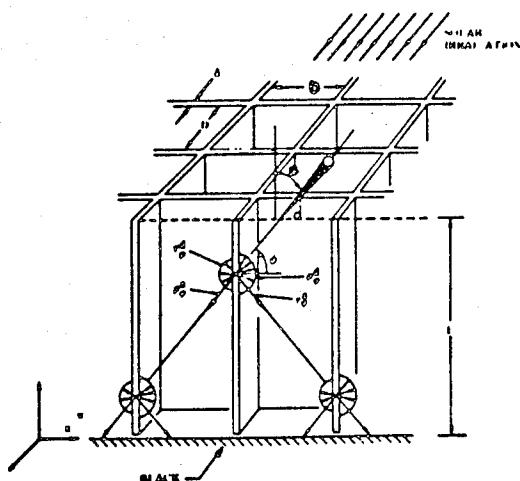


Fig. 1a

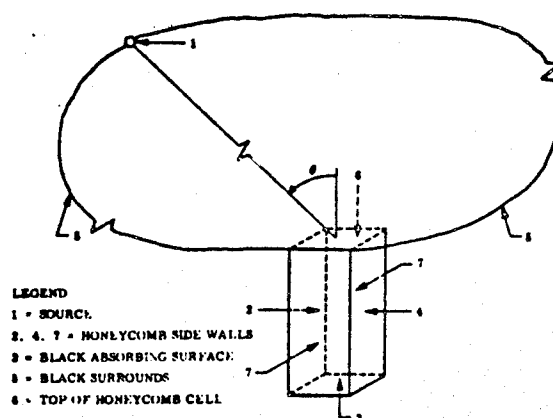


Fig. 1b

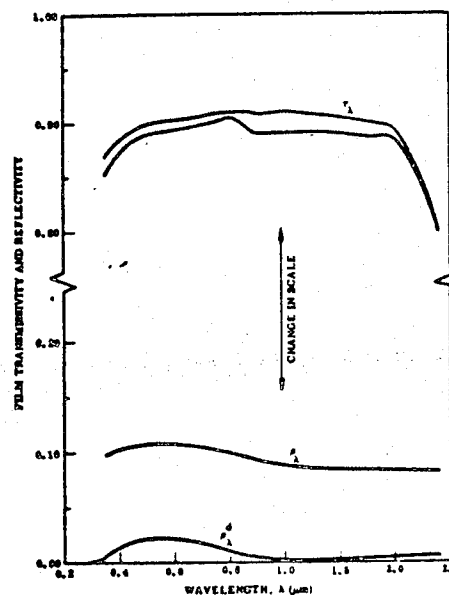


Fig. 2

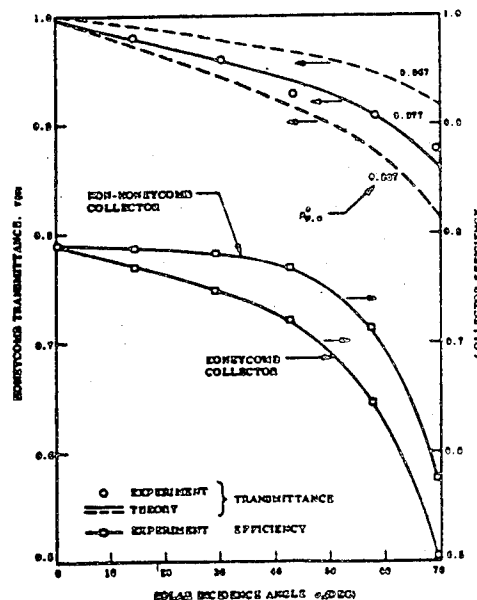


Fig. 3

A.5 USE OF LEXAN AND KAPTON HONEYCOMBS TO INCREASE SOLAR COLLECTOR EFFICIENCY

Experimental results are presented for Lexan and Kapton honeycomb solar collectors tested in an outdoor test facility. Performance is given in terms of both instantaneous and diurnal efficiencies. Results for various honeycomb aspect ratios are given to show the effect of aspect ratio on collector performance. A comparison is made between honeycomb and nonhoneycomb collectors with flat black absorbers. The results show that collector efficiency is increased significantly so that a cost savings may be realized through utilization of a properly designed plastic honeycomb solar collector.

K. N. Marshall
and
R. K. Wedel

INTRODUCTION

The need for development of low-cost solar collectors with improved efficiency at the higher temperatures required for both heating and cooling of buildings has led researchers to consider placing a transparent honeycomb structure between the absorber plate and transparent cover to reduce the reradiation and convection losses (1, 2). Initial experimental studies by Cunningham and Streed (3) with Mylar honeycomb demonstrated the potential for transparent honeycomb to increase collector efficiency. Recent work performed by Hollands (4) and by Baldwin, et al. (5) has shown that convection heat loss from the collector can be suppressed through the use of properly designed honeycomb. In addition, experimental studies by Buchberg and Edwards (6) on glass honeycomb and by Marshall, et al. (7) on plastic honeycomb has shown that the reradiation losses from collectors with flat black absorbers are reduced by using honeycomb structures.

Although the potential for increasing the efficiency of a solar collector utilizing transparent honeycomb has been demonstrated, a suitable honeycomb material has not been commercially available. Also, an optimum honeycomb aspect ratio (L/D) has not been established and verified experimentally through collector testing. Consequently, a program was carried out at the Lockheed Palo Alto Research Laboratory under ERDA sponsorship to evaluate various transparent plastic materials for honeycomb application in solar collectors. The primary objective of this work was to develop a high-performance collector design for use in the temperature range of 82°C (180°F) to 122°C

(250°F) using thin transparent plastic honeycombs.

During this program, a number of plastic materials, including Mylar,* Tedlar,* Lexan,** Kapton,* and FEP Teflon,* were evaluated. Their optical and thermal properties were determined, and performance characteristics of collectors using these materials were established on the basis of analytical models. Honeycomb sections were fabricated for various aspect ratios. The plastic honeycomb sections were installed in collector test units, and testing was performed under ambient weather conditions in the Lockheed Solar Test Facility in Palo Alto, California.

Although the overall program included evaluation of the five plastic films mentioned above, over both selective black and flat black coated absorbers, the discussion in this paper is limited to the performance of Lexan and Kapton over flat black absorbers on which extensive testing has been completed. Insufficient test data on Mylar, Teflon, and Tedlar honeycombs at this time prevent a meaningful discussion and comparison of results for these materials. Test results on the selective coated/honeycomb collectors require further analysis. Such information will be reported in future publications.

HONEYCOMB MATERIALS AND CONFIGURATIONS

Various honeycomb sections were fabricated using Lexan (polycarbonate) Type 8073-112 and Kapton (polyimide). The configurations tested are shown in Table I. A standard hexagonal cell configuration produced by Hexcel, Dublin,

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Palo Alto, California 94304

* duPont Trademark.

** General Electric Trademark.

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Table I
HONEYCOMB MATERIALS AND CONFIGURATION TESTED

Material	Cell Diameter		Film Thickness		Aspect Ratio			
	(cm)	(in.)	(cm)	(in.)	L/D	L/D	L/D	L/D
Lexan	0.477	3/16	0.0076	0.003		2	5	10
Lexan	0.953	3/8	0.0076	0.003	1	2	5	
Kapton	0.953	3/8	0.0025	0.001	1	2	5	

California, was used in construction of the honeycomb as shown in Figure 1.

Lexan honeycomb was found to be the easiest to fabricate; therefore, honeycomb specimens of this material were constructed in two different cell diameters (i.e., 0.477 and 0.953 cm, as shown in Table I). It was thus possible to compare the performance between two different cell diameters for the same material and equivalent L/D ratios. The range of aspect ratios from one to ten for the Lexan honeycomb provided a sufficiently wide range to study for collector application. Although the cell diameters used for the study were chosen on the basis of ease of fabrication and the availability of existing tooling, they represent sizes typical for collector applications.

The plastic film thicknesses as shown in Table I were selected on the basis of initial considerations of optical properties, material availability, and application of existing honeycomb fabrication methods. The optical properties for the films as measured at Lockheed (8) are given in Table II.

The solar transmission of each honeycomb section is shown in Figure 2, along with other honeycomb materials, as a function of aspect ratio and solar incident angle. These results, originally reported in Ref. 7, illustrate the advantage of using transparent materials for honeycomb collectors. The more transparent materials provide significantly better diurnal performance than the opaque honeycombs. Kapton honeycomb has a lower transmission than Lexan because the Kapton film absorbs more of the incident solar flux (see Table II).

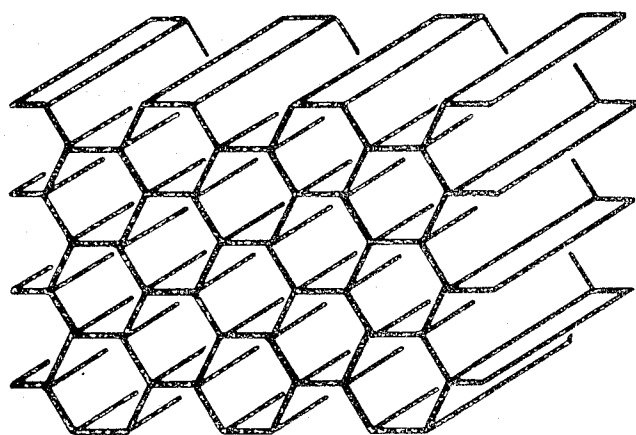


Fig. 1. Hexagonal core honeycomb

Table II
SINGLE FILM OPTICAL PROPERTIES

Material	Film Thickness (cm)	Solar Spectrum			Infrared Spectrum		
		τ_s	ρ_s	α_s	τ_{IR}	ρ_{IR}	$\epsilon_{IR} = \alpha_{IR}$
Lexan	0.0076	0.91	0.09	≈ 0	0.52	0.09	0.39
Kapton	0.0025	0.69	0.12	0.19	0.46	0.12	0.42

The effective emittances of Lexan and Kapton honeycombs over a flat black absorber are shown in Figure 3. These results (7) show the decrease in effective emittances as the aspect ratio increases; thus, the reradiation energy losses are reduced significantly by Lexan and Kapton honeycomb/flat black collectors having large aspect ratios. A

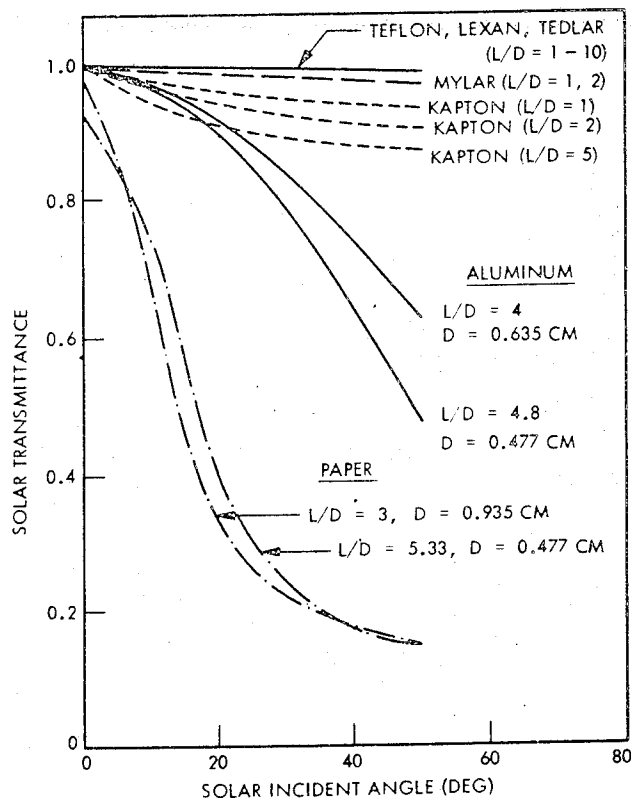


Fig. 2. Solar transmission of various honeycombs.

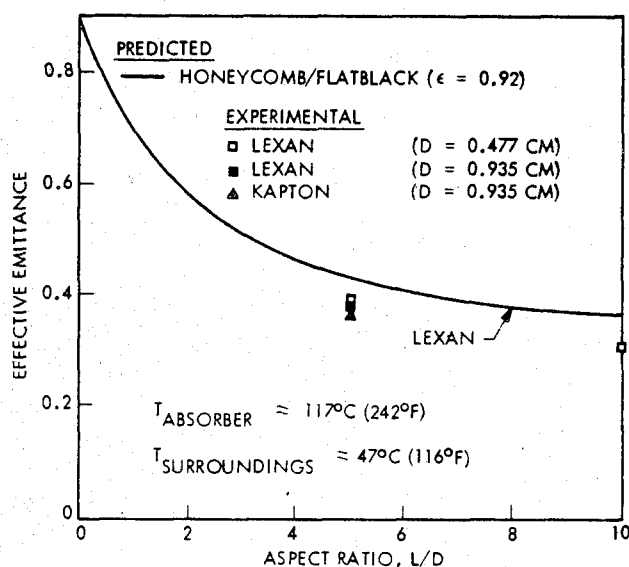


Fig. 3. Measured and predicted effective emittance for Lexan and Kapton honeycombs.

final selection of the optimum aspect ratios depends on the tradeoffs between material costs, transmission losses, and suppression of the reradiation and convection heat losses.

COLLECTOR CONFIGURATIONS

A number of collector test units containing Lexan and Kapton honeycombs over flat black absorbers were assembled along with single- and double-glazed non honeycomb collectors. The honeycomb collectors were designed to accept a range of L/D ratios from one through ten so that simultaneous testing could be conducted on a number of different configurations.

The absorber panels for all collectors were 43 × 127 cm (17 × 50 in.) in size. These panels were 0.16 cm (1/16 in.) thick, parallel flow, aluminum "Roll-Bond" procured as off-the-shelf items from Olin Brass Company, East Alton, Illinois. Each panel was precoated with a flat black paint and assembled into the collector test units such that the spacing between the absorber and cover glass was approximately equal to the "L" dimension of the plastic honeycomb. The honeycomb sections were assembled in each collector so that they were in contact with the absorber plate and had not more than 0.813 mm (1/32 in.) clearance between the cover glass and honeycomb. The flat black absorber coating consisted of Chemglaze Z306 polyurethane black which had an α_s of 0.96 and an ϵ of 0.92.

One glass cover of 0.32 cm (1/8 in.) double-strength Fourco "Clearite H" tempered glass with a solar transmittance of 0.85 for air mass two was used on all honeycomb collectors. The glass aperture size for each collector was the same as the absorber plate size, 43 × 127 cm.

The collectors without honeycomb were essentially identical to those with honeycomb except that a single spacing of 2.54 cm (1 in.) was maintained between absorber

plate and glass cover. For the nonhoneycomb collector with two covers, a spacing of 2.54 cm was set between the two covers and between the inner cover and the absorber plate.

TEST EQUIPMENT

Testing was performed in accordance with procedures recommended by NBSIR 74-635 (9) at the Lockheed Solar Collector Test Facility in Palo Alto, California (37° 27' North Latitude). This facility provides the capability for simultaneous testing of several individual collectors. The facility has instrumentation for continuous data acquisition of collector inlet and outlet temperatures, ambient air temperature, relative humidity, wind velocity and direction, and solar irradiation. Absolute inlet and outlet fluid temperatures are measured with platinum resistance thermometers (PRT) which have a calibration accuracy of $\pm 0.05^\circ\text{C}$ and a repeatability of $\pm 0.02^\circ\text{C}$ over the temperature range being measured. Data from these measurements are used to calculate collector efficiency. To provide a backup for the PRTs in case of instrument failure, differential temperatures between inlet and outlet are measured using copper-constantan differential thermocouples. The inlet-to-outlet temperature differences measured by the differential thermocouples are within $\pm 0.3^\circ\text{C}$ of that measured by the PRTs. Real-time monitoring is accomplished using copper-constantan thermocouples. During testing, the inlet temperature of each collector is controlled to a predetermined value using resistance heaters installed in the inlet fluid line.

The flow of heat transfer fluid is set and maintained through each individual collector by a positive displacement, controlled volume pump. A separate pump is used for each collector. Each pump maintains the flow rate to the set value with an accuracy of $\pm 1\%$ and combines the functions of a pump, measuring instrument, and control valve into one system. Each pump is calibrated periodically at different fluid temperatures throughout the test program to verify the flow rate setting.

The heat transfer fluid consists of 50%/50% mixture by volume of Prestone® II and distilled water. To prevent boiling at the higher operational temperatures, the system is operated under pressure.

Total incident solar energy is measured with an Eppley PSP pyranometer. Diffuse sky radiation is measured using a Spectrolab SR-75 pyranometer with a shadow band to shade the direct component of solar energy.

A 100-channel automatic data-acquisition system, with an accuracy of 0.05% of reading, is used to display and record all test data. Data are recorded on printed tape for real-time monitoring and on punched paper tape for data reduction by computer. Strip chart recorders are used for continuous monitoring of inlet and outlet temperatures, solar irradiation, and weather conditions. The instrumentation used to control, measure, and record test data is within the specifications required by NBSIR 74-635.

TEST PROCEDURE

Tests were simultaneously conducted on up to four collectors to provide a direct comparison of performance. Both honeycomb and nonhoneycomb collectors with flat black coatings were tested. The parameters controlled during the tests included fluid inlet temperature, flow rate, and collector orientation with respect to the solar vector. Measurements were made of inlet and outlet fluid temperatures, ambient air temperature, wind velocity and direction, relative humidity, and both total and diffuse solar irradiation using pyranometers located in the plane of the collectors. Testing was done in accordance with NBSIR 74-635 (9) and was carried out over a three-month period starting September 9, 1975, and ending December 9, 1975. Tests were conducted only on those days when steady-state solar conditions could be achieved for at least two hours near solar noon.

Testing was conducted for various inlet temperatures over the range of 40°C (103°F) to 120°C (247°F). The flow rate of the heat transfer fluid was maintained constant during all tests, with the flow rate for the four collectors being 30.36, 31.86, 33.31, and 33.59 kg/hr, respectively. The flow rates were established by setting the adjustment dial on the various pumps. Once set and calibrated, the dial settings remained fixed throughout the test program. Pump calibration was done by weighing a given amount of heat transfer fluid over a specific time interval. The calibrations were checked at various times during the test program.

A majority of the tests were performed with the tilt angle of the test rack adjusted so that each collector surface was normal to the solar vector at solar noon. Over the three-month period, the tilt angle varied from 30 to 58 degrees as measured from the horizontal plane.

RESULTS AND DISCUSSION

Test results are presented for the honeycomb and nonhoneycomb collectors in terms of both instantaneous efficiency and diurnal performance. Instantaneous efficiency is given as a function of $(T_{FL} - T_{AMB})/I$, i.e., $\Delta T/I$. Diurnal performance is presented in terms of energy per unit area collected over several hours of operation for a given day. All results reported herein are for collectors with flat black absorbers.

Result of instantaneous efficiencies for the Lexan and Kapton honeycomb collectors and single-glazed nonhoneycomb collectors are presented in Figures 4, 5, and 6. The four collectors presented in each figure were tested simultaneously on the same test rack. The resultant effects of different honeycomb aspect ratios on collector efficiency are vividly displayed by the data presented. In each figure, a similar pattern is observed with the efficiencies decreasing linearly as $\Delta T/I$ increases. These results show the dependence of collector efficiency on the temperature difference between the absorber plate and ambient air when

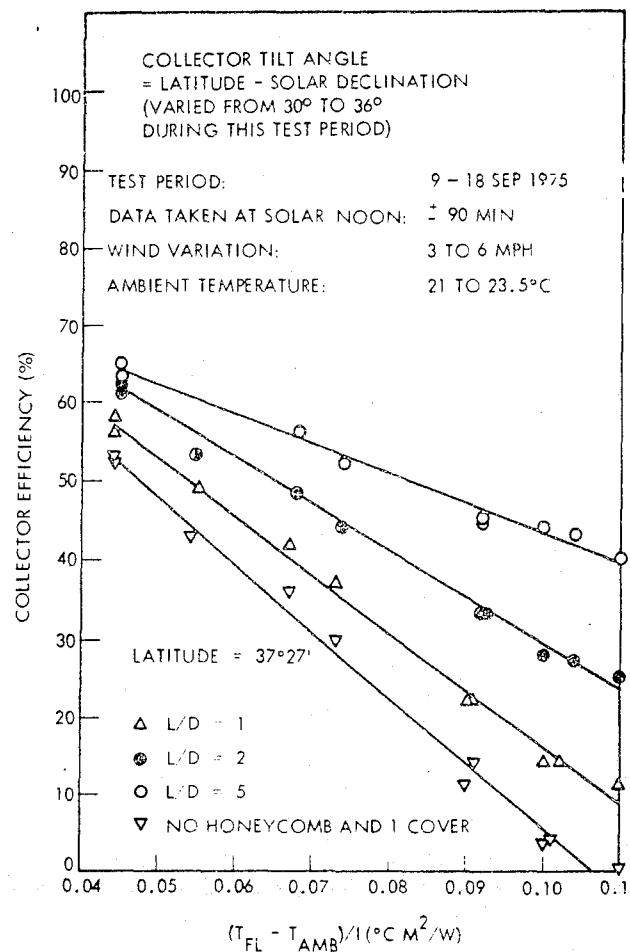


Fig. 4. Efficiency of 0.953-cm cell-diameter Lexan honeycomb collectors with flat black absorber.

the incident solar energy does not vary significantly during a test series. In all cases, collector efficiency increases as the honeycomb aspect ratio (L/D) gets larger, with the nonhoneycomb collector exhibiting the poorest performance. The increase in honeycomb collector efficiency is due to a reduction in convection and reradiation heat losses as the L/D ratio increases. The reduction in radiation losses can be related back to Figure 3, where the effective emittance of the honeycomb/absorber system decreases as the honeycomb L/D ratio increases. For the test conditions and honeycomb aspect ratios greater than 2 as reported herein, convection suppression, as defined by Hollands, *et al.* (10), has occurred. For such cases, the heat transfer through the air is by conduction and, as such, is linearly dependent on honeycomb cell length (L).

Figures 4, 5, and 6 show the increasing influence on efficiency by the honeycomb aspect ratio as the $\Delta T/I$ term increases. As collector temperatures rise, the radiation term becomes more significant. Therefore, the reduced effective emittance of the larger L/D honeycombs becomes an important factor in reducing collector heat losses.

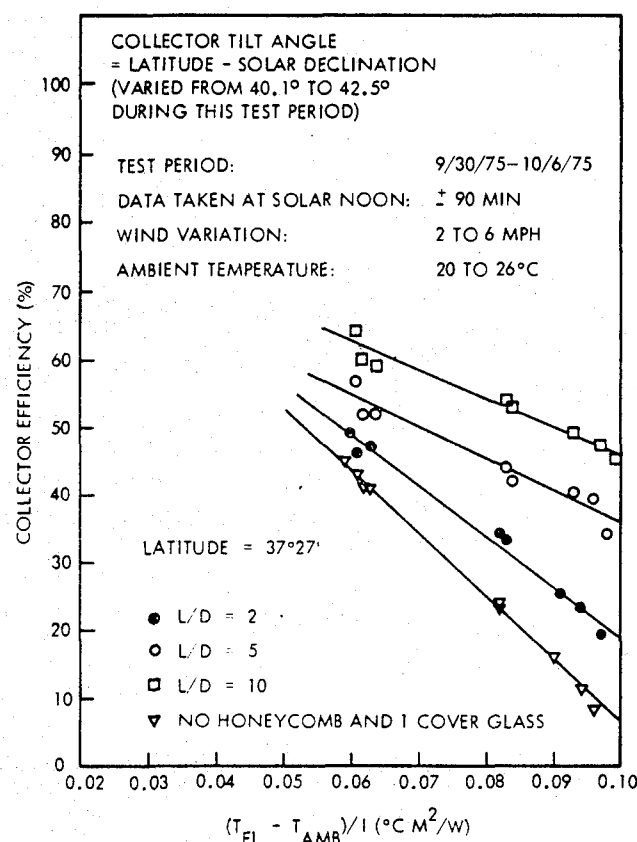


Fig. 5. Efficiency of 0.477-cm cell-diameter Lexan honeycomb collectors with flat black absorber.

When the performance of Kapton honeycomb (Figure 6) is compared with that of Lexan honeycomb (Figure 4), which has an equivalent cell diameter, it is seen that the efficiencies are essentially the same for aspect ratios of 1 and 2. However, for an aspect ratio of 5, the Lexan appears to be slightly higher. This difference illustrates the absorption characteristics of the Kapton for solar energy and the dependence of Kapton's performance on solar incident angle for large L/D ratios. The efficiency of Lexan and Kapton honeycomb collectors will not be the same for equivalent cell diameters and aspect ratios when the solar vector is normal to the collector surface, since Kapton will absorb at least 20% of the diffuse incident solar radiation.

The differences noted between the nonhoneycomb systems shown in Figures 4, 5, and 6 are attributed partly to data scatter from test to test and partly to variations in ambient conditions.

Figure 7 presents a comprehensive comparison of the instantaneous efficiencies of honeycomb and nonhoneycomb collectors. Both Lexan honeycomb with cell diameters of 0.477 and 0.953 cm are included. With the exception of the double-glazed nonhoneycomb collector, all the curves are from Figures 4 and 5. From Figure 7, a number of significant observations can be made.

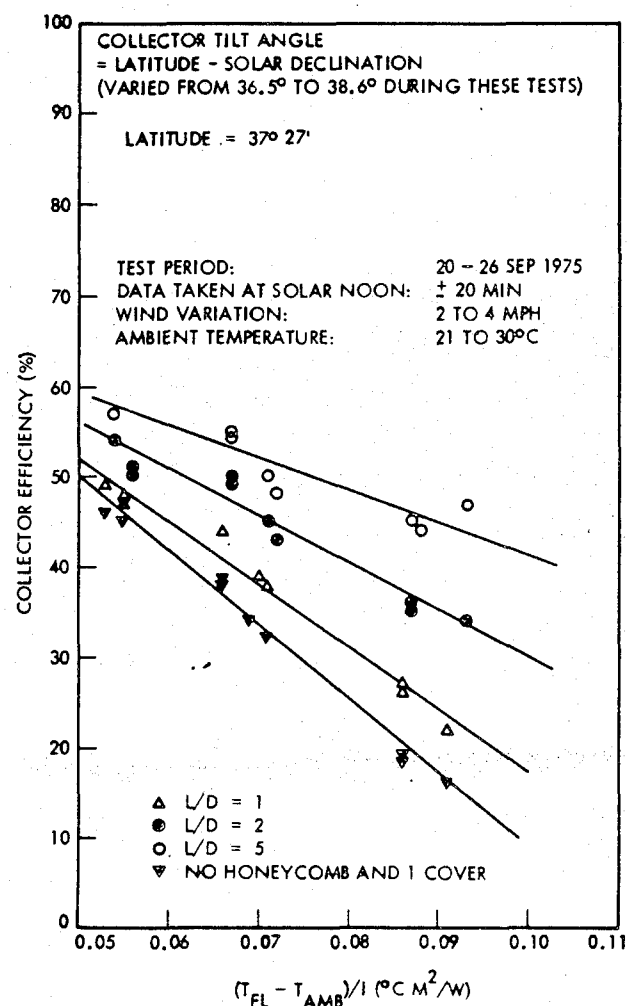


Fig. 6. Efficiency of 0.953-cm-diameter cell Kapton honeycomb collector with flat black absorber.

A major observation is that collectors equipped with Lexan honeycomb with $L/D = 5$ and having either 0.477- or 0.953-cm cell diameters have much better efficiency than double-glazed nonhoneycomb flat black collectors. The nonhoneycomb collector has essentially the same efficiency as the 0.953-cm diameter, $L/D = 2$ honeycomb collector shown in Figure 4. All honeycomb collectors tested were better performers than the single-glazed nonhoneycomb collector.

When the two best performing Lexan honeycomb collectors are compared, it is seen that the collector with $L/D = 10$ and $D = 0.477$ cm has higher efficiency than the one with $L/D = 5$ and $D = 0.953$ cm. Since convection is suppressed and the cell lengths are equal, the difference in efficiency is attributed to the difference in radiation heat loss due to change in effective emittances as a function of the L/D ratio. A similar conclusion can be drawn when a comparison is made of the results of the two Lexan honeycomb collectors having $L/D = 1$, $D = 0.953$, and $L/D = 2$, $D = 0.477$.

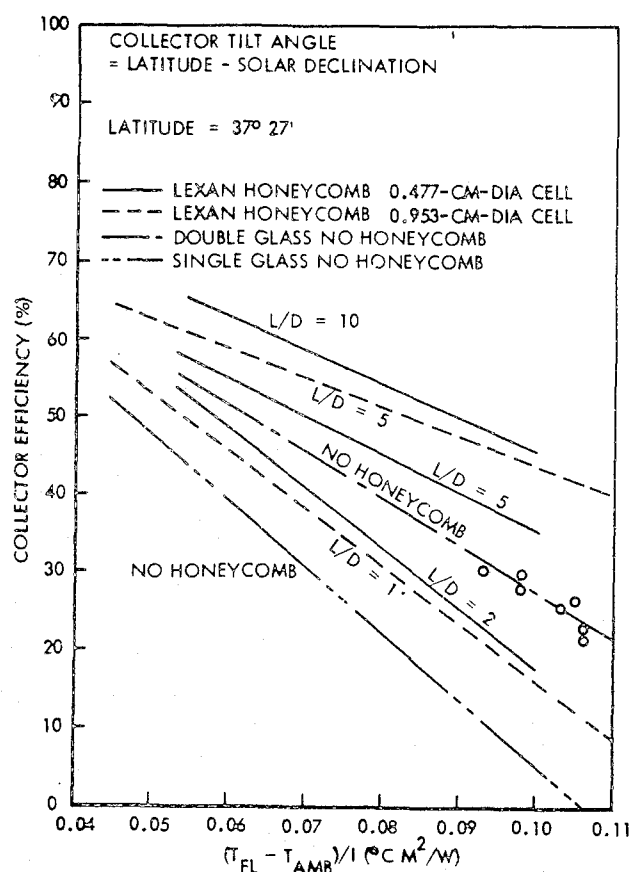


Fig. 7. Comparison of collector efficiencies for Lexan honeycomb and nonhoneycomb designs with flat black coating.

When a comparison is made of honeycomb collectors having the same L/D and different cell diameters, it is seen in Figure 7 that the system with the larger cell diameter is more efficient. Since the effective emittances of the two Lexan honeycombs with equivalent L/D ratios are essentially equal, the difference in efficiency is due to conduction through the air and is, therefore, a function of L .

Figure 8 shows the diurnal performance of 0.477-cm cell diameter Lexan honeycomb/flat black collectors for various aspect ratios. A comparison is made with a single-glazed nonhoneycomb collector. It is significant to note the continued higher performance for the Lexan honeycomb collectors at high solar incident angles. The Lexan honeycomb collector with $L/D = 5$ collected energy for approximately two hours longer over the day than did the nonhoneycomb system. The good performance at high incident angles substantiates solar transmission results presented in Figure 2.

A comparison of performance between a honeycomb collector and a double-glazed nonhoneycomb collector is shown in Figure 9. Although the daily distribution of solar is not symmetrical for the date shown, the results show that the honeycomb collector had significantly better performance. An extrapolation of these curves indicates that the honeycomb collector will collect almost twice as much

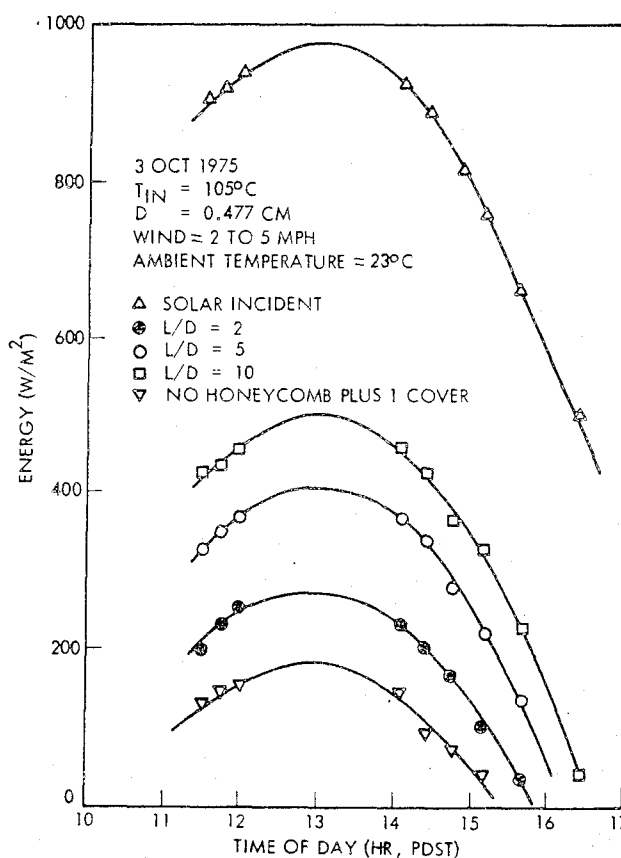


Fig. 8. Diurnal energy collected by 0.477-cm-diameter cell Lexan honeycomb/flat black collectors of various aspect ratios.

energy during the day than the nonhoneycomb double-glazed collector. It is recognized that this assumption is based on limited data and that further studies are required to refine the figures.

Figure 10 presents the diurnal performance of 0.953-cm-diameter Kapton honeycomb for various aspect ratios. Again, the honeycomb systems collect more total energy than a single-glazed nonhoneycomb system. This figure illustrates the decreased performance expected of the Kapton honeycomb collector with $L/D = 5$ at off-normal incident angles. Within approximately $1\frac{1}{2}$ hr ($22\frac{1}{2}^\circ$), the honeycomb systems with $L/D = 5$ and $L/D = 2$ are about equal in instantaneous performance.

A comparison of energy collected over several hours of operation for Lexan and Kapton honeycomb collectors with $L/D = 5$ and $D = 0.953$ cm is presented in Figure 11. The results show a better "all-day" performance for the Lexan unit, which can be attributed to Lexan honeycomb's good transmission at high angles of solar incidence. As discussed before, the instantaneous efficiency of both collectors at solar noon should not be the same, since Kapton absorbs the diffuse sky radiation at a rate of about 20%. Kapton then decreases more rapidly at higher incident angles as it absorbs part of the direct solar radiation.

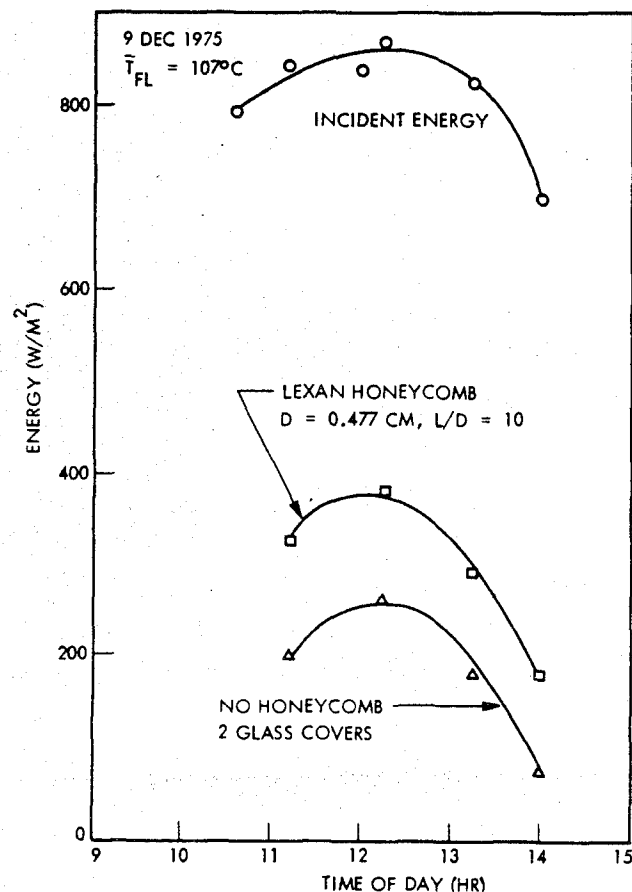


Fig. 9. Comparison of diurnal energy for Lexan honeycomb and double-glazed nonhoneycomb over flat black absorber.

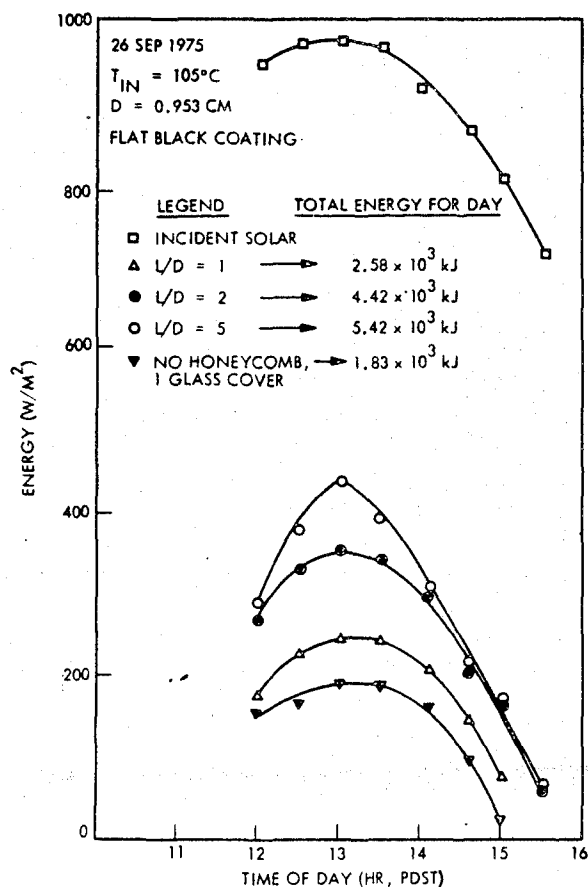


Fig. 10. Diurnal energy collected with Kapton honeycomb collectors.

CONCLUSIONS

From the results presented, it is concluded that honeycomb placed between a flat black absorber and transparent cover provides considerable improvement in the performance of solar collectors over the operational temperature range of 70 to 120°C. Both the instantaneous efficiencies and diurnal performances of properly designed honeycomb collectors are increased over those obtained with a single- or double-glazed nonhoneycomb flat black collector. The honeycomb achieves the improved performance by reducing the convection and reradiation losses. The magnitude of heat loss reduction is a strong function of the honeycomb aspect ratio.

Both Lexan and Kapton honeycomb collectors have equivalent instantaneous efficiencies near solar noon. However, due to the solar-absorbing characteristic of Kapton film, the efficiency for a Kapton honeycomb collector is lower than that for a Lexan honeycomb collector at larger solar incident angles.

The performance of honeycomb collectors is dependent on both the L/D ratio and the cell length (L). The L/D ratio governs the effective emittance of the honeycomb/absorber system and thereby influences the reradiation heat losses.

The convection heat loss is governed by the cell length once the aspect ratio providing convection suppression has been selected. With convection suppression, the heat loss through the air gap is by conduction and is a linear function of the cell length.

Maximum efficiency for honeycomb collectors is achieved using only one transparent cover glass. Therefore, a cost tradeoff can be made between the cost of the honeycomb and the cost of the second glass cover typically used on conventional high-performance flat-plate collectors. The cost tradeoff combined with the improved performance of a honeycomb collector results in a potential cost reduction for the overall solar collector system. For the case of the lower cost, low-temperature plastics such as Lexan or Mylar, the cost savings can be significant. However, in using plastics such as Lexan for honeycomb applications, thermal protection methods must be employed to protect the honeycomb from the high temperatures often encountered during periods when the heat transfer fluid is not flowing (e.g., pump or power failures).

Preliminary cost studies indicate that the high-temperature plastics such as Kapton are presently not cost competitive due to high material costs. Such honeycombs

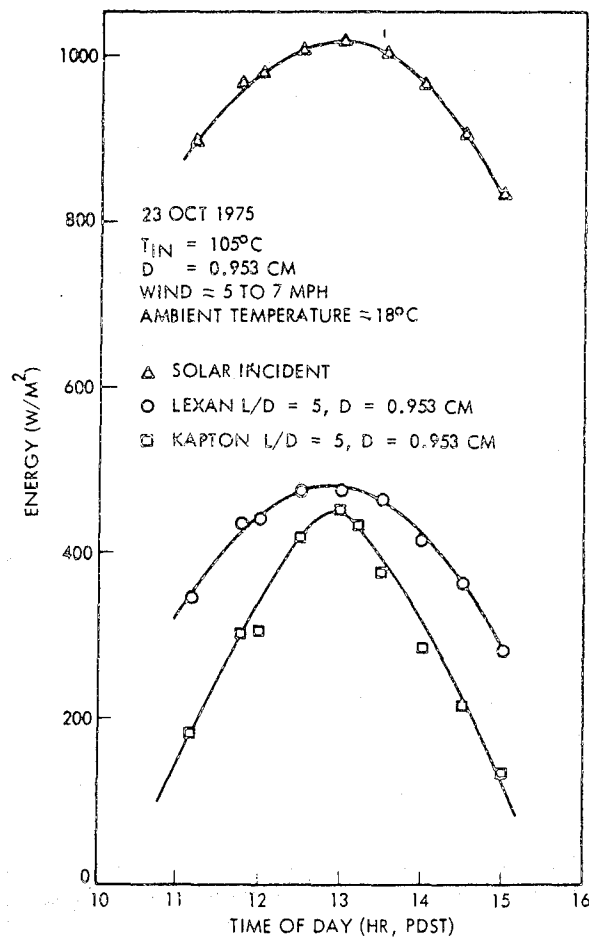


Fig. 11. Comparison of diurnal energy collected by Lexan and Kapton honeycomb/flat black collectors.

can, however, become cost competitive if methods are developed for reducing the amount of material required for producing the cellular structure.

In summary, properly designed plastic honeycombs provide significant improvements in solar collector performance. Many of the available plastics are presently cost competitive and can provide substantial savings in initial collector costs. However, further development is required to optimize honeycomb geometry and improve manufacturing techniques leading to more efficient use of materials and additional reduction in costs.

ACKNOWLEDGMENTS

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performance of the test program, and data reduction.

The work reported herein was accomplished at the Lockheed Research Laboratory, Palo Alto, California, Development Administration ERDA Contract E(04-3)-1081.

NOTATION

D	= Honeycomb cell diameter, m
I	= Incident solar radiation, W/m^2
L	= Honeycomb cell length, m
T_{AMB}	= Air temperature, $^{\circ}C$
T_{FL}	= Average fluid temperature in collector, $^{\circ}C$
α	= Absorptivity
ϵ	= Emissivity
ρ	= Reflectivity
τ	= Transmissivity

Subscripts

s	= Solar spectrum
IR	= Infrared spectrum

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EXPERIMENTAL PERFORMANCE OF FLAT PLATE SOLAR COLLECTORS WITH
VARIOUS COVER MATERIALS WITH AND WITHOUT TRANSPARENT PLASTIC HONEYCOMB*

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Abstract

An experimental program was performed in which the efficiency of a flat plate collector was measured as a function of various collector cover materials. The materials chosen as candidate covers were FEP Teflon*, Tedlar**, and high transmittance glass. Efficiency data was also measured for the collector with a Lexan† honeycomb between the cover and the absorber plate. The results showed that the optimum cover material was dependent upon the operating temperature.

experimental studies by Buchberg, et al ³ on glass honeycomb and by Marshall, et al ⁴ on plastic honeycomb have shown that the reradiation losses from collectors with flat black absorbers are reduced by using honeycomb structures. Testing on a full scale collector with Lexan honeycomb ⁴ verified that honeycombs increase a collector's efficiency. Also, recent data ⁵ indicate that Lexan honeycomb gives the best performance of the low temperature plastic honeycombs. Therefore, when used with a collector with a plastic cover, a honeycomb can lower the heat losses to a comparable value of a glass covered, honeycomb collector.

Introduction

Depending upon their end use, solar collectors utilize either one or two covers. In general, swimming pool collectors for midsummer application need no cover; however, collectors used to extend the swim season have one cover of glass or plastic, as do collectors used for space heating and hot water heating in mild climates. For heating in cold climates, hot water heating, and for air conditioning applications, collectors are used that have either a selective black absorber with one or two covers or a flat black absorber with two covers. The cover materials used are either glass or plastic. For high-temperature collectors glass covers are preferred because they are opaque in the longer wavelength (infrared) region and improve the efficiency by reducing radiation of energy to the sky. The plastics, on the other hand, are cheaper and lighter and therefore offer an attractive alternative when their optical properties are similar or better than those of glass.

For a collector with a flat black absorber, the radiation and the convection heat losses can be decreased by placing honeycomb between the absorber plate and the cover. Initial experimental studies by Cunningham and Stroed ¹ with Mylar honeycomb demonstrated the potential for transparent honeycomb to increase collector efficiency. Recent work performed by Hollands ² and by Buchberg ³ has shown that convection heat loss from the collector can be suppressed through the use of properly designed honeycomb. In addition,

Discussion

Cover Material

Glass, Tedlar, and FEP Teflon are three of the most popular materials presently used for covers for solar collectors. Glass covers are usually tempered and, to maximize solar transmission, have minimum iron content. Covers made of Tedlar and Teflon are usually 0.0127 cm (5 mil) or less in thickness. Used in this effort was 0.475 cm (3/16") thick ASC Sunadex[‡] glass, Tedlar 0.0102 cm (4 mil) thick, and FEP Teflon 0.00265 cm (1 mil) thick. In Table 1 the optical properties of the three materials are listed. While the FEP Teflon has the highest solar transmission, it also has the highest long wavelength transmission. The Tedlar and glass have nearly equal solar transmissions, but Tedlar is partially transparent in the long wavelength spectrum where the glass is opaque. Considering these differences in optical properties, different covers will give the most efficient non-honeycomb flat black collector for different temperature applications. At low temperatures an FEP Teflon cover should be best since heat losses will be low. However, at high operating temperatures the radiation heat loss becomes important. Therefore, the glass covered collector should be the most efficient since the glass prevents energy being radiated from the absorber plate directly to the sky. The addition of honeycomb to a collector with any of the covers enhances its performance. However, the improvement in performance at high temperatures of a collector with a plastic cover will be greater than with a glass cover since one of the major drawbacks of a plastic cover, the large

* This work was accomplished under the sponsorship of the Solar Heating and Cooling Research Branch of ERDA Contract E(04-3)-1256.

** du Pont

† General Electric

‡ ASC Industries

TABLE 1
RADIATION PROPERTIES OF COVERS

	ASG Glass	FEP Teflon	Tedlar
Thickness: mm	4.76	0.0254	0.102
in.	3/16"	.001	.004
<u>SOLAR SPECTRUM</u>			
Transmittance	0.91	0.95	0.90
Reflectance	0.08	0.04	0.08
Absorptance	0.01	0.01	0.02
<u>LONG WAVELENGTH SPECTRUM</u>			
Transmittance	0	0.58	0.33
Reflectance	0.15	0.07	0.08
Emittance	0.85	0.35	0.59

radiation loss directly from the absorber plate to the atmosphere, is markedly decreased. Therefore, the performance of the honeycomb collectors with various covers should be similar at high temperatures, while at low temperatures the FEP Teflon covered collector should outperform the others due to its higher solar transmission.

Collector Configuration and Test Procedure

The absorber panels for the collectors were 43x127 cm (17x50 in.) in size. These panels were 0.16 cm (1/16 in.) thick, parallel flow, aluminum "Roll-Bond" procured as off-the-shelf items from Olin Brass Company, East Alton, Illinois. Each panel was coated with a flat black paint and assembled into the collector test units such that the spacing between the absorber and cover was 5.08 cm (2"). The flat black absorber coating consisted of 3M Black Velvet paint with a solar absorptivity of 0.98 and an infrared emissivity of 0.90. The honeycomb sections were assembled in each collector so that they were in contact with the absorber plate and not more than 0.813 mm (1/32 in.) from the cover glass. The honeycomb was 0.00762 cm (3 mil) thick Lexan made by the Hexcel expanded core technique. The honeycomb had a 0.953 cm (3/8") cell diameter and was 4.76 cm (1 7/8") long for an aspect ratio of five. The back and sides had 3" of fiberglass insulation.

The testing was performed in accordance with NBS procedures at the Lockheed Solar Collector Test Facility in Palo Alto, Ca. ⁶ Three separate series were run in which two identical flat black absorber collectors were used, one with honeycomb and the other without honeycomb. In one series of tests the covers were glass; the second series had Tedlar covers, and the third had FEP Teflon covers.

Collector performance was determined over the temperature range of fluid inlet temperature from 27°C (80°F) to 120°C (248°F). Tests were simultaneously conducted on the two collectors to provide a direct comparison of performance. The parameters controlled during the tests included fluid inlet temperature, flow rate, and collector orientation with respect to the solar vector. Measurements were made of inlet and outlet fluid temperatures, ambient air temperature, wind velocity and direction, relative humidity, and both total and diffuse solar irradiation using pyranometers located in the plane of the collectors. The flow rate of the heat trans-

fer fluid was maintained constant during all tests. The tilt angle of the test rack was adjusted so that each collector surface was normal to the solar vector at solar noon.

Results

The instantaneous efficiencies of collectors with Tedlar, Teflon, and glass covers with and without Lexan honeycomb are shown in Figure 1. Without honeycomb the Teflon covered collector was the most efficient of the three at low temperatures due to the high solar transmittance of Teflon. At high temperatures the Tedlar and Teflon covered collectors performed equally well; however, the efficiency of the glass covered collector was appreciably higher. With Lexan honeycomb, the Teflon covered collector was the most efficient collector over the entire temperature range with the difference in efficiency greatest at low temperatures. The Tedlar and glass covered collectors' performances were the same, indicating that the honeycomb did equalize the heat losses for the two designs. Also, the performance of honeycomb, plastic covered collectors was forty percent greater than the non-honeycomb collector at the high temperatures (fluid temperature minus air temperature divided by incident solar radiation greater than 0.08°C-M²/W).

The diurnal performances for an inlet fluid temperature near 90°C with Teflon, Tedlar, and glass covers are shown in Figures 2, 3 and 4, respectively, and summarized in Table 2. The tests were on different days with slightly different weather conditions and tilt angles; however, the results for all covers are similar. The use of honeycomb more than doubled and in one case more than tripled the efficiency compared to the non-honeycomb collector. Also, the efficiency with honeycomb is approximately the same with all covers, while with no honeycomb a glass cover gives a better performance than a Tedlar or Teflon cover.

TABLE 2

DIURNAL PERFORMANCE

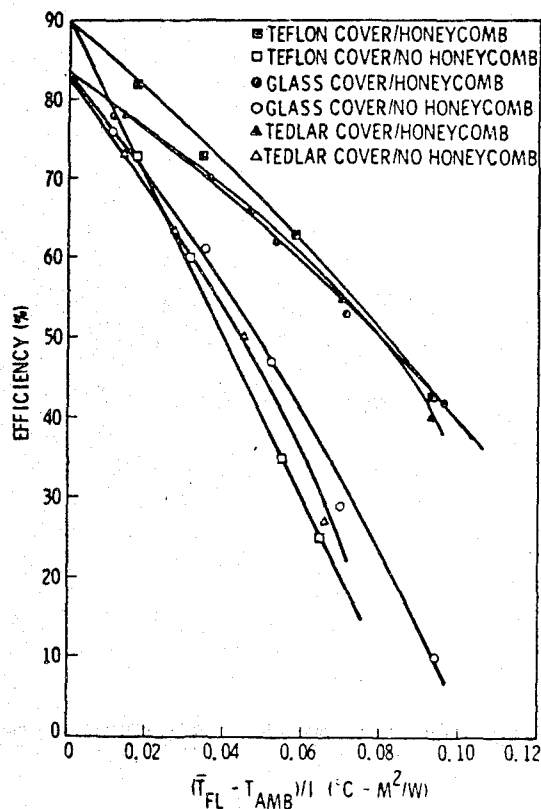
	Useful Energy Collected (W-Hr/M ²)	Efficiency
A) Teflon Cover		
No Honeycomb	1005	.13
Honeycomb	3290	.42
B) Tedlar Cover		
No Honeycomb	1200	.16
Honeycomb	3230	.43
C) Glass Cover		
No Honeycomb	1430	.18
Honeycomb	3210	.41

Conclusions

The test results verified the theory concerning the effect of both cover materials and honeycombs on collector performance. The conclusions are:

- o At low temperatures a cover's solar transmission is its dominant optical property

FIGURE 1. EFFICIENCY COMPARISONS FOR VARIOUS COVERS FOR HONEYCOMB AND NON-HONEYCOMB FLAT BLACK COLLECTORS

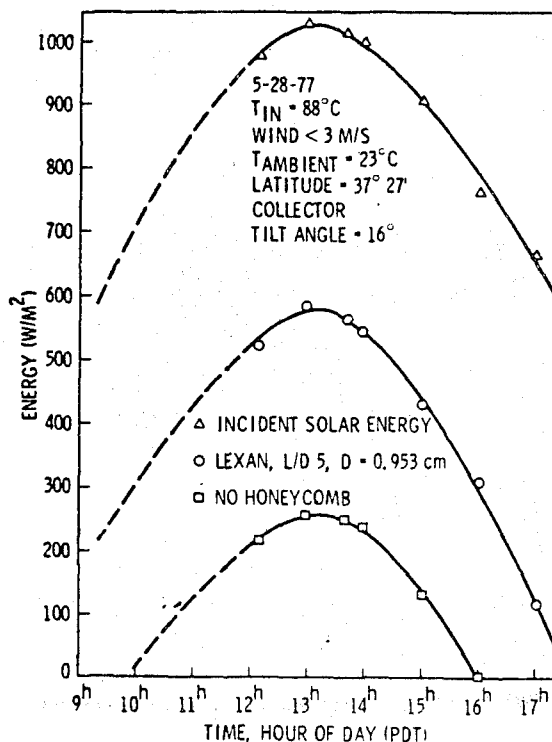


- o At high temperatures an IR opaque cover gives best performance for flat black, non-honeycomb collectors.
- o A honeycomb structure placed between the absorber plate and a cover improves the performance of solar collectors, with the greatest performance increase for collectors with FEP Teflon covers.
- o A honeycomb causes a flat black collector with FEP Teflon cover to be more efficient over the entire temperature range than either a Tedlar or glass covered collector.

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FIGURE 2. DIURNAL PERFORMANCE OF A TEFLON COVERED COLLECTOR WITH FLAT BLACK ABSORBER PLATE WITH AND WITHOUT LEXAN HONEYCOMB



3. Buchberg, H., D. K. Edwards, and J. D. Mackenzie, Transparent Glass Honeycomb Structures for Energy Loss Control, SAN/1084-75/1, Final Report for ERDA Contract E(04-3)-1084, UCLA, Los Angeles, Ca., March 1976.
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6. Hill, J. E., and Kusuda, T., Method of Testing for Rating Solar Collectors Based on Thermal Performance, U.S. Department of Commerce, Springfield, Virginia, NBSIR 74-635, December 1974.

FIGURE 3. DIURNAL PERFORMANCE OF TEDLAR COVERED
FLAT BLACK COLLECTOR WITH AND WITHOUT
LEXAN HONEYCOMB

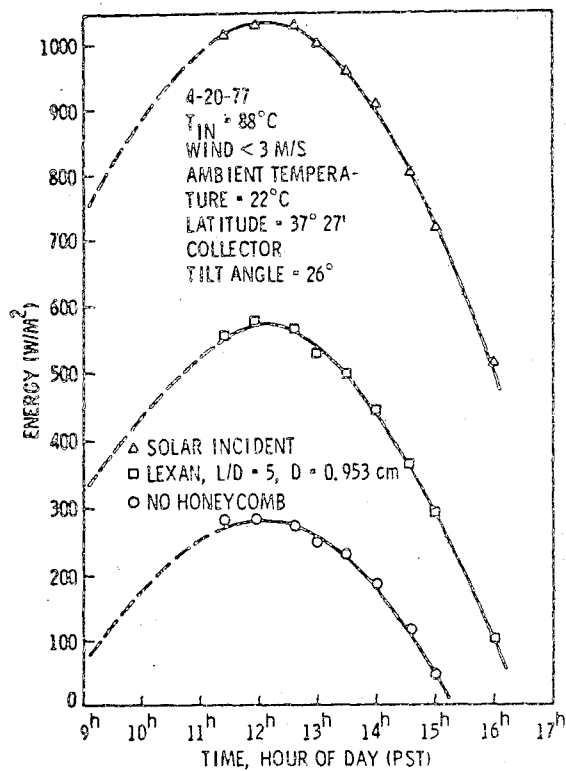


FIGURE 4. DIURNAL PERFORMANCE OF A GLASS COVERED
FLAT BLACK COLLECTOR WITH AND WITHOUT
LEXAN HONEYCOMB

